Design of a High Powered LED Driver

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ABSTRACT

Research has shown that LED lighting products have greater energy efficiency, longer lifespans, and lower heat outputs than compared with traditional lighting technologies. An estimated growth of 45 percent per year through 2019 for the LED lighting market should provide a wider variety of LED related products to consumers. The goal of this project; to create a driving circuit that powers a set of high powered LEDs. The implementation of LEDs significantly reduces the power consumption in comparison with other types of light such as incandescent bulbs or CFLs, therefore saving the consumer money.

I. INTRODUCTION

Most sources of light located in a typical home consist of incandescent lamps or compact fluorescent lamps (CFLs). These light sources have proved inefficient in terms of power use and output lighting when compared to light emitting diodes [1]. Light emitting diodes are semiconductor devices that emit light when electrical current passes through it. A light emitting diode or LED consists of two types of materials called P-type semiconductors and N-type semiconductors. Current flows from the p-side to the n-side of the diode. The area in between both materials is called the P-N junction. Charge carriers known as electrons and holes flow into the junction with different voltages. When one of the electrons meets a hole, it falls into a lower energy level and releases energy in the form of a photon.

The typical power consumption of an incandescent bulb is 60W and they last an average of around 1000 hours. Compact fluorescent lamps (CFLs) last an average of around 8000 hours and consume about 15 watts of power [13]. Incandescent bulbs are very inefficient since a lot of their energy is wasted as heat. A drawback of CFLs is that they contain mercury which is highly toxic. This makes CFLs hazardous and hard to dispose of properly without damaging the environment. The LED is much more efficient than the previously mentioned alternatives. They have lower power consumption and longer lifespans. LEDs last an average of 50,000 hours or more and draw less than 8 watts of power.

A minimum of 800 lumens is chosen as the luminous flux output by the system. On average, a typical 60W incandescent light bulb produces 800 lumens of light [13]. A compact fluorescent light bulb producing the same light output as the incandescent light bulb only requires about 15W of power. An LED light bulb having an output of 800 lumens only requires about 8W to power it. If each of these bulbs were expected to remain on for about 5 hours per day for a year and the price per KWh of power used is 18.02 cents in the state of California for September 2014 [14], then the LED bulb would cost about $2.63 to operate. The compact fluorescent bulb would require about $4.93 to operate for 5 hours every day for a year. The incandescent bulb would require $19.73 to operate for 5 hours every day for a year. Different topologies for the DC to DC Converter are researched in order to achieve a final design for the LED driver [8].

The only problem with LED lighting is that it costs more than incandescent or CFL bulbs. Replacing every fixture with LED bulbs would prove costly to the homeowner. The system for this project provides a driving circuit that powers a set of LEDs that run much more efficiently than standard lighting methods and provides it at lower costs.

Figures 1-3 show the Gantt charts for the LED driver project. The project is estimated to be finished around the fifth week of the spring quarter. The remaining weeks in the spring quarter are to be spent working on the report for the project and to make small changes in the circuit that can improve its efficiency.

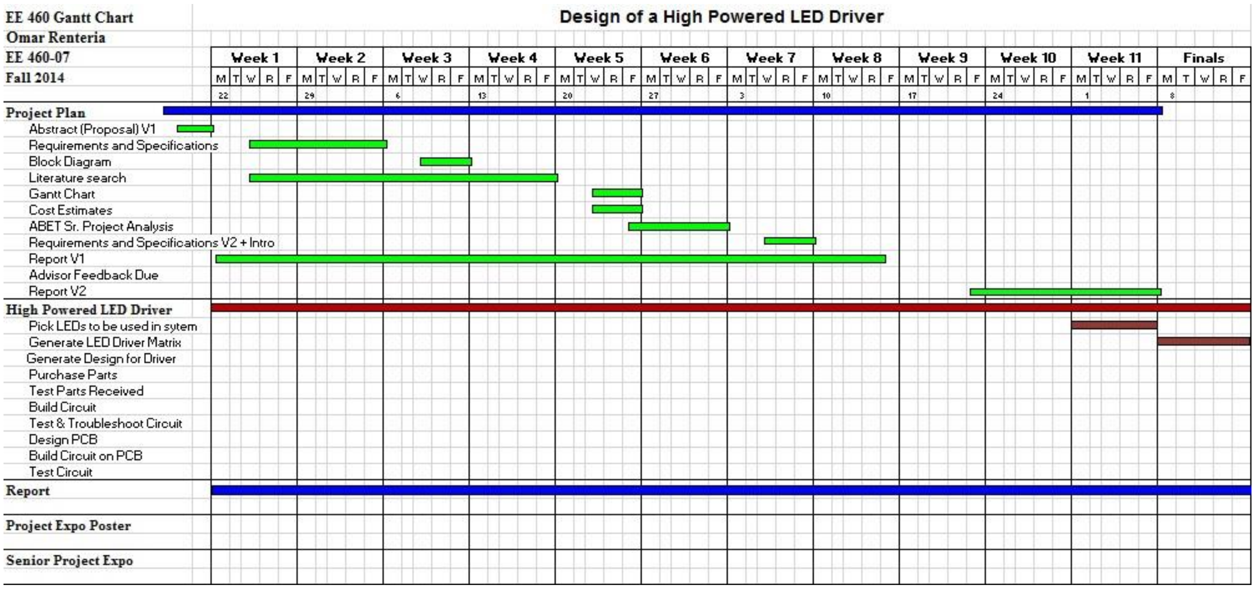

FIGURE 1

LED DRIVER GANTT CHART FALL 2014

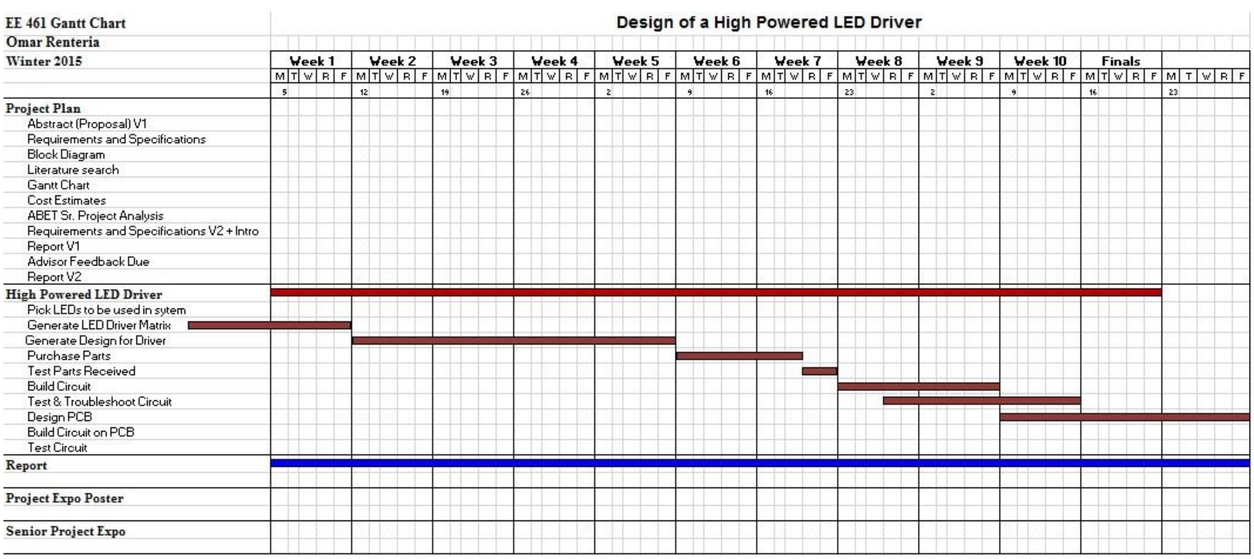

FIGURE 2

LED DRIVER GANTT CHART WINTER 2015

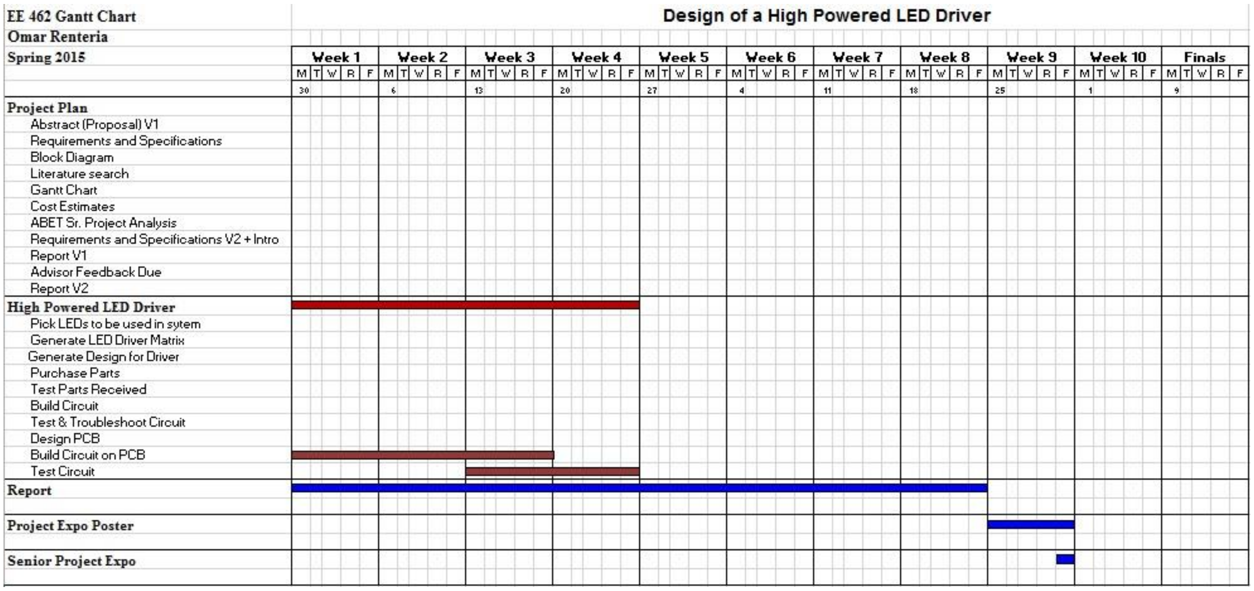

FIGURE 3

LED DRIVER GANTT CHART SPRING 2015

II. CUSTOMER NEEDS, REQUIREMENTS, and SPECIFICATIONS

This system targets students, office workers, and just about anyone who requires a long lasting and efficient source of light. The overall cost of the system needs to be cheaper than similar products in the market or it will not attract the consumers' attention. The customers need a product that requires as little maintenance as possible. This is achieved through the use of LEDs. LEDs on average last about 50,000 hours or more [13]. If the LEDs are estimated to stay on for 5 hours each day in every year then they will need to be replaced every 27 years. Incandescent bulbs on average last about 1,200 hours [13], and they typically only last for about a year. Through the use of LED technology, the customer saves money by not having to purchase replacement bulbs every year. The datasheet of a randomly selected high-powered LED specifies a maximum junction temperature of 150˚C [1]. The high temperature can significantly impact the performance of the LEDs. The high temperatures can permanently damage the LED with no heat sinks present to cool it down.

TABLE 1

DESIGN OF A HIGH POWERED LED DRIVER REQUIREMENTS AND SPECIFICATIONS

Marketing Requirements	Engineering Specifications	Justification
1	Total system cost to manufacture under $130.	Cheaper than commercially available products with the same functionality as this product.
1,3	Dimensions of the driving circuit under 3.8" x 2.5" x 1".	System fits in the base of a standard lamp.
2,4	Junction temperature lower than 120˚C.	Reduced efficiency of the LEDs occurs with higher temperatures and also run the risk of permanent damage.
1,2,4	Should have a maximum input power of 20W.	Ensures that the LEDs operate at their highest efficiency.
1,4	System should produce a minimum of 800 lumens.	The standard 60W LED replacement bulb emits an average amount of visible light equivalent to 800 lumens.
1, 3, 5	Total system should weigh under 8 lbs.	Weight includes that of the luminaire. Weighs less than similar products in the market.
4, 6	Color temperature higher than 3000K	Typically used in libraries or office areas

Marketing Requirements

1. System should have a low cost
2. System should operate at low temperatures
3. As small as possible
4. System should have a high output power
5. System as light as possible
6. System produces warm white light

III. FUNCTIONAL DECOMPOSITION

Figure 4 shows the Level 0 block diagram for the LED Driver. A typical 120V 60Hz household outlet provides the input to the system. Output of the system is the light produced by the LEDs.

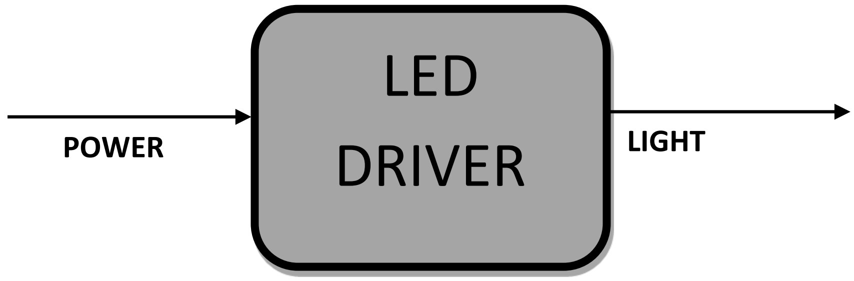

FIGURE 4
LEVEL 0 BLOCK DIAGRAM

TABLE 2
FUNCTIONALITY TABLE FOR THE LEVEL 0 BLOCK DIAGRAM

MODULE	High powered LED Driver
INPUTS	Power: 120 V AC 60HZ
OUTPUTS	Light: Minimum luminous intensity of 800 Lumens
FUNCTIONALITY	To power a set of high powered LEDS efficiently with minimal power loss.

Figure 5 shows the Level 1 block diagram for the LED driver circuit. The bridge rectifier takes the input which is from a household outlet rated at 120 V AC and output a direct current, which can be used by the DC-to-DC converter to achieve the right voltage needed in order to power the LEDs. The output of the DC-DC converter is adjusted depending on the configuration of the LEDs and the amount used. The forward voltage of each LED at 1A is 3.7V [2]. The DC-to-DC converter being used in this circuit is a boost converter. The boost converter can produce an output voltage that is greater than its input [11].

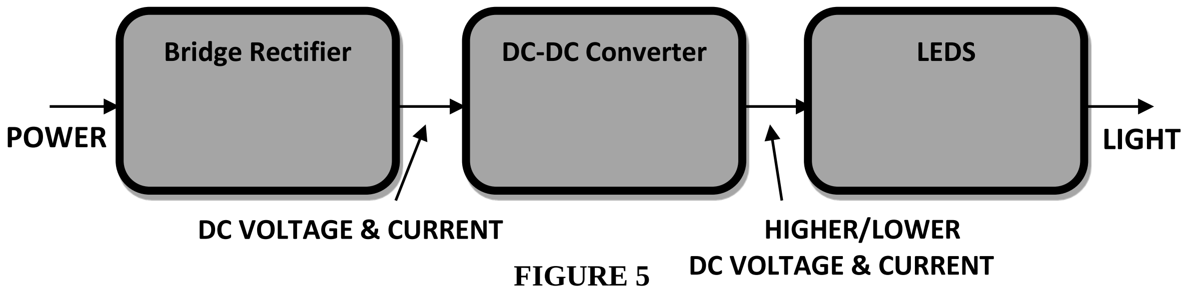

FIGURE 5
LEVEL 1 BLOCK DIAGRAM

TABLE 3
FUNCTIONALITY TABLE FOR THE LEVEL 1 BLOCK DIAGRAM (BRIDGE RECTIFIER)

MODULE	Bridge Rectifier
INPUTS	Power: 120 V AC 60HZ
OUTPUTS	DC voltage and current
FUNCTIONALITY	Conversion of alternating current (AC) into direct current (DC)

Table 2 describes the inputs and outputs for the LED driver circuit. The output of the driver will be light with a minimum intensity of 800 lumens. Table 1 shows the engineering specifications for the whole system. The color temperature of the LEDs will be around 3000k which is typically used in libraries or office environments. The color temperature was chosen because the system is intended to be used in a household. Tables 3-5 show the functionality tables for each of the three separate modules that make up the LED driver. The tables describe the inputs/outputs and the overall functionality of each module.

TABLE 4

FUNCTIONALITY TABLE FOR THE LEVEL 1 BLOCK DIAGRAM (DC-DC CONVERTER)

MODULE	DC-DC Converter
INPUTS	DC voltage and current
OUTPUTS	Higher DC voltage and current than input
FUNCTIONALITY	Converts a source of direct current from one voltage level to another.

TABLE 5

FUNCTIONALITY TABLE FOR THE LEVEL 1 BLOCK DIAGRAM (LEDS)

MODULE	LEDS
INPUTS	DC voltage and current to power LEDS 3.7V at 1A per LED [2]
OUTPUTS	Light
FUNCTIONALITY	Semiconductor device that emits light when a voltage is applied to its leads.

Table 6 shows the Costs estimate table for the whole driver system. The project is was finished the week before finals. A total of around 7-10 hours were put into the project per week depending on the workload for the other classes. This includes labor put into the project by the student and also time spent by the advisor providing feedback on the project. This accumulates to a total of about 260 hours of labor put into the creation of the project. Hourly wage was chosen to be around $20, so total costs in labor come to a total of $5200. The AC to DC converter was purchased from Digikey. Most of the equipment needed to complete this project was found in the project labs, but some money had to be spent on additional equipment such as solder, flux, ESD safe tweezers, and an antistatic wrist strap. The parts list includes the LEDs needed for this system, the heat sink, and all the parts required to produce the DC to DC Converter.

TABLE 6
COSTS ESTIMATE TABLE

Costs Estimate	
Materials	**Cost**
PCB	$112
Parts	$78.98
Equipment	$39.79
LEDs	$41.45
Labor	$5,200
Total:	$5,472

IV. DESIGN

The first step in the design process of the LED driver is to pick the type of LED that can be used and the quantity. I settled with picking out a product from all the different types of LEDs produced by Cree. Cree is a multinational manufacturer of semiconductor light emitting diodes. The reason for picking this manufacturer is that the prices of their products are reasonable and are of good quality.

The Cree XR-E was chosen for the driver because of its price and its light output of 251 lumens at 4 Watts [2]. The next step was to choose the correlated color temperature of the LED since various options were available. The correlated color temperature (CCT) describes how the color of the light appears from the light source which is measured in kelvins. The scale ranges from 1000K which is very red to 10,000K which is very blue. The higher up the scale the light goes, the closer it resembles blue daylight. Color temperature does not describe the temperature of the light source but rather it describes the color it produces. Table 7 shown below shows the color temperature range. There is no wrong choice for color temperature, it all depends on the consumer's choice for light. A typical incandescent light bulb emits a yellowish color with a temperature range between 2700K-3300K [15]. After some research it was determined that a cool white color temperature would be used. Cool white colors are typically used in office, study, and retail environments and they provide a cleaner and brighter feel.

The next step was to decide how many of the Cree XR-E LEDs to use in the system. The goal is to power a lamp that outputs a higher or equal amount of light than a regular incandescent bulb. A typical 60 Watt incandescent light bulb emits about 800 lumens of visible light. In order to achieve a light source that emits an equal or greater amount, I will have to wire 4 of those LEDs in series to achieve a final output of 1004 lumens. This is about a 25.5% increase in luminous flux than a traditional 60 Watt incandescent bulb.

The forward voltage of each LED is around 3.5V with a maximum drive current of 0.7A. This requires around 10W to power the LEDs at close to their maximum point.

TABLE 7

COLOR TEMPERATURE TABLE

Kelvins	Type	
1,000K	Candlelight Red/Yellow	Very Warm
2700K	Conventional Lamp - Yellow	Warm
3000K		Warm White
4000K	Halogen/CFL - Blue	White
5000K		Cool White
6000K		Daylight
10,000K	Blue Sky - Blue	Very Cool

The next step is to choose a topology for the driver. Many different DC-to-DC converter topologies exist but only the most common were examined. The first topology examined is the Buck converter. Its pros are that it contains only one switch voltage drop, has low-ripple current in the output-filter capacitor and it has the lowest peak current of any switching-regulator configuration [16]. Its cons are that the output voltage must be less than the input voltage and that it requires a high-side switch. The advantages and disadvantages for each of the other topologies examined are listed on Tables 8-12. The design of the driver along with the chosen topology is outlined in the next section.

TABLE 8

BUCK CONVERTER CHARACTERISTICS

Non-Isolated	
Forward:	Energy goes from input, through the magnetics & to the load simultaneously
Step Down(Buck):	Output voltage is lower than input, and of same polarity
Advantages	**Disadvantages**
Low Switch Stress	Potential overvoltage if switch is shorted
Small output filter	High side switch drive required
Low ripple	High input ripple current
Remarkably efficient 95%	

TABLE 9

BOOST CONVERTER CHARACTERISTICS

Non-Isolated	
Flyback:	Energy goes from input & stored in the magnetics. Later, it is released from magnetics to the load.
(Non-inverting)Step Up(Boost):	Output voltage is higher than input.
Advantages	**Disadvantages**
Low input ripple current	High peak collector current
	Regulator loop hard to stabilize
	High output ripple
	Unable to control short-circuit current

TABLE 10

SEPIC CONVERTER CHARACTERISTICS

Non-Isolated	
Flyback:	Energy goes from input & stored in the magnetics. Later, it is released from magnetics to the load.
(Non-inverting)SEPIC:	Output voltage can be lower or higher than input.
Advantages	**Disadvantages**
Low ripple input current	Switch has high peakand rms current which limit output power
Step-up/down with n ratio	2 caps used have high ripple current requirements(low ESR)
Capacitive isolation protects against switch failure	CCM makes loop stabilization difficult
	High output ripple

TABLE 11

BUCK-BOOST CONVERTER CHARACTERISTICS

Non-Isolated	
Flyback:	Energy goes from input & stored in the magnetics. Later, it is released from magnetics to the load.
(Inverting)Buck-Boost:	Output voltage magnitude that is either greater than or less than the input.
Advantages	**Disadvantages**
Voltage inversion without transfomer	Regulator loop hard to stabilize
High frequency operation	High side switch drive required
	High output ripple
	High input ripple current

TABLE 12

CUK CONVERTER CHARACTERISTICS

Non-Isolated	
Flyback:	Energy goes from input & stored in the magnetics. Later, it is released from magnetics to the load.
(Inverting Boost-Buck)Cuk:	Output voltage magnitude that is either greater than or less than the input.
Advantages	**Disadvantages**
Low ripple input & output current	High drain current
Capacitive isolation protects against switch failure	Intermediate capacitor has high ripple current requirement (low ESR)
	High voltage required for the switch

V. LED DRIVER

Various companies produce integrated circuits for driving LEDs. Some of these companies include Texas Instruments, Maxim Integrated, Linear Technology, STMicroelectronics, Fairchild Semiconductor and many others. Several different integrated circuits from each of these manufacturers were researched to come up with a decision on which one should be used. I finally decided to pick the MAX16834 current-mode high-brightness (HB) LED driver produced by Maxim Integrated. One of the reasons for choosing this IC is due to the fact that it drives an n-channel PWM dimming switch that allows for LED PWM dimming and also it can be configured to run in different topologies such as boost, boost-buck, SEPIC, and high-side buck. Another reason is that the MAX16834 has an Evaluation kit which can be used to mount the components on in case that the PCB design for the driver does not end up working well. The component side of the MAX16834 evaluation board can be seen in Figure 6.

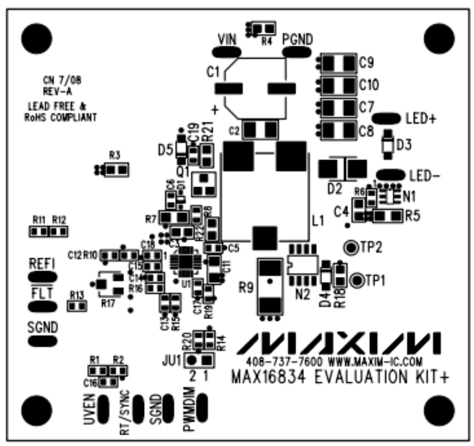

FIGURE 6

MAX16834 EVALUATION BOARD

I decided to use a boost topology which can be seen below in Figure 7. The input to the IC is from a 5V power supply manufactured by Triad Magnetics. The power supply will provide a maximum current of 4A for a max output power of 20W. The efficiency of this particular IC is 92%. The components for the circuit which is shown in Figure 7 are determined by a set of equations which are located on the datasheet.

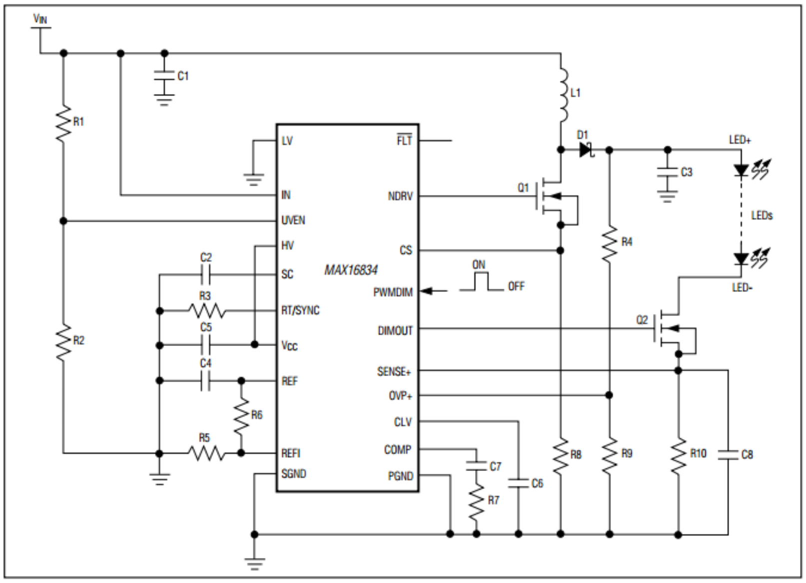

FIGURE 7
BOOST LED DRIVER

The first step in the design process of the MAX16834 IC is to determine the switching frequency of the internal oscillator. Resistor RT can be calculated by using Equation 1 with the desired switching frequency.

$$f_{OSC}\ (kHz) = \frac{5000k\Omega}{RT(k\Omega)} \times\ (kHz)$$ **Equation 1**

The next step was to set the UVLO threshold for the MAX16834. The Under voltage Lockout allows the IC to turn on when the V_{UVEN} exceeds 1.435V. The UVLO threshold is set by resistors R1 and R2. It is recommended to use a 10kΩ resistor for R2 and this just leaves R1 to be calculated by using Equation 2.

$$V_{UVEN} = 1.435V(R1 + R2)/R2$$ **Equation 2**

The overvoltage threshold is set by resistors R9 and R4. The overvoltage circuit responds quickly once it is triggered to protect the circuitry from being damaged. The overvoltage circuit is activated when the voltage on OVP+ with respect to LV exceeds 1.435V.

Equation 3

$$V_{OV} = 1.435V(R4 + R9)/R9$$

The next step is to program the LED current using the voltage on REFI and the LED current-sense resistor R10.

$$I_{LED} = \frac{V_{REF} \times R5}{R10 \times (R6 + R5) \times 9.9}(A)$$ **Equation 4**

I_{LED} is set to be operating at 0.7A from the CREE X-RE datasheet [2], V_{REF} is given from the MAX16834 datasheet as 3.7V. Resistor R10 is chosen so that the regulation voltage across it does not exceed 0.3V. If the voltage across it exceeds 0.3V the LED short-circuit protection circuit is activated. R5 is also picked making sure that the desired value is available for sale with tolerances of 1% from the chosen value. All that is needed to program the LED current is to enter all the previously mentioned values into Equation 4 and solving for R6. The closest value which could be obtained was a resistor with a resistance of 9.1kΩ.

The next step is to determine the maximum duty cycle of the MAX16834 IC, which will then be used to calculate the maximum average inductor current, peak-to-peak inductor current ripple, and the peak inductor current.

$$D_{MAX} = \frac{V_{LED} + V_D - V_{INMIN}}{V_{LED} + V_D - V_{FET}}$$ **Equation 5**

V_{LED} is the forward voltage of the LED string in volts. In this case since I will be using four CREE X-RE LED's operating at 3.5V at 0.7A, the forward voltage will be 14V. V_D is the forward drop of the rectifier diode D1 which is approximately 0.6V. V_{INMIN} is the minimum input supply voltage which in this case will be set to 4.75V. V_{FET} is the average drain to source voltage of the MOSFET Q1 when it is on, an approximate value of 0.2V is recommended by the datasheet to initially calculate D_{MAX}. Once the power MOSFET is selected, a more accurate value of the maximum duty cycle can be calculated.

The next step was to determine the minimum inductance value for the inductor L1. A few values are needed before being able to calculate the inductance value using Equation 9 shown below. First I needed to find the maximum average inductor current which can be calculated by using Equation 6. I_{LED} is set to be 0.7A from the CREE XR-E datasheet [2] as was previously mentioned.

$$IL_{AVG} = \frac{I_{LED}}{1 - D_{MAX}}$$ **Equation 6**

$$\Delta I_L = IL_{AVG} \times 0.3 \times 2$$ **Equation 7**

The maximum average inductor current can now be used to obtain the peak-to-peak inductor current ripple which can be calculated by the use of Equation 7. This equation allows the peak-to-peak inductor ripple to be about 30% of the average inductor current.

$$IL_P = IL_{AVG} + \frac{\Delta I_L}{2}$$ **Equation 8**

Equation 8 shown above represents the peak inductor current measured in amperes.

$$L = \frac{(V_{INMIN} - V_{FET}) \times D_{MAX}}{f_{SW} \times \Delta I_L}$$ **Equation 9**

Once values are calculated from Equations 6-8, then Equation 9 can finally be used to calculate the minimum inductance value. V_{INMIN} as was mentioned before is the minimum supply voltage which in this project is set to 4.75V. V_{FET} as was also previously mentioned is the average drain to source voltage of the MOSFET Q1. An approximate value of about 0.2V is used initially. F_{sw} is the switching frequency which is f_{osc} which was calculated in Equation 1. The chosen inductor has to have a minimum inductance greater than the calculated value and the current rating of the inductor should be higher than IL_P from Equation 8.

$$R8 = \frac{0.25}{(IL_P \times 1.25)}\Omega$$ **Equation 10**

Equation 10 can be used to find the value for the switch current-sense resistor. The 0.25 in the numerator is the minimum peak current-sense threshold in volts. The peak inductor current is multiplied by a factor of 1.25 to provide a 25% margin to account for tolerances. The $I_{SAT\ of}$ the inductor should be higher than 0.35V/R8.

The next step is to determine the value of the output capacitor. The function of the output capacitor is to reduce the output ripple to acceptable values. The parasitic inductance (ESL), the equivalent series resistance (ESR), and the bulk capacitance of the output capacitor all contribute to the output ripple. In order to reduce the ESL and ESR effects, multiple capacitors may be connected in parallel to achieve the required bulk capacitance.

$$C_{OUT} \geq \frac{I_{LED} \times 2 \times D_{MAX}}{\Delta V_{OUTRIPPLE} \times f_{SW}}$$ **Equation 11**

$$ESR_{COUT} < \frac{\Delta V_{OUTRIPPLE}(\Omega)}{(IL_P \times 2)}$$ **Equation 12**

The output capacitance can be calculated by using Equation 11 shown above. $\Delta V_{OUTRIPPLE}$ is the output voltage ripple in volts. The output voltage ripple is chosen to be 150mV which is the same as the input, the input voltage ripple was obtained directly from the datasheet of the Triad Magnetics power supply being used in this project. The ESR of the output capacitor can be calculated from Equation 12. The chosen capacitance has to be higher than the calculated value obtained in Equation 11, and the ESR of the capacitor has to be less than the value obtained in Equation 12.

Equation 13 can be used to calculate the RMS current rating for the output capacitor.

$$I_{COUT(RMS)} = \sqrt{\begin{matrix}(IL_{AVG} \times (1 - D_{MAX}))^2 \times D_{MAX} \\ +(IL_{AVG} \times D_{MAX})^2 \times (1 - D_{MAX})\end{matrix}} \quad \textbf{Equation 13}$$

The input capacitor C1 bypasses the ripple current drawn by the converter and helps reduce the amplitude of high-frequency current being conducted to the input supply. The parasitic inductance (ESL), the equivalent series resistance (ESR), and the bulk capacitance of the capacitor all contribute to the input ripple. Low-ESR capacitors that can handle the maximum input RMS ripple current should be used.

$$C_{IN} \geq \frac{\Delta I_L}{4 \times \Delta V_{IN} \times f_{SW}} \quad \textbf{Equation 14}$$

The input capacitance can be calculated directly from Equation 14. ΔV_{in} is the input ripple, which is obtained directly from the Triad Magnetics power supply datasheet. The ESR of the input capacitor is calculated with the use of Equation 15.

$$ESR_{CIN} < \frac{\Delta V_{IN}}{\Delta I_L \times 2} \quad \textbf{Equation 15}$$

Equation 16 is used to find the RMS current rating of the input capacitor.

$$I_{CIN(RMS)} = \frac{\Delta I_L}{2\sqrt{3}} \quad \textbf{Equation 16}$$

The value for the slope compensation capacitor can be found using Equation 17. V_{LED} is the voltage of the LED string, which is 14V in this case. Slope compensation is added to converters with peak current-mode control operating in continuous conduction mode (CCM) to avoid current loop instability. The capacitor is charged with a 100µA current source, which is shown in the equation and discharged at the beginning of each switching cycle.

$$C2 = \frac{3 \times L \times 100 \times 10^{-6}}{(V_{LED} - V_{INMIN}) \times R8 \times 2} \quad \textbf{Equation 17}$$

The switching MOSFET Q1 should have a drain-to-source voltage rating higher than the value calculated from Equation 18. The voltage rating should be sufficient to withstand the maximum output voltage together with the voltage drop of the diode D1 and any overshoot that might be caused by parasitic capacitances or inductances. V_D is the forward voltage drop of the diode D1.

$$V_{DS} = (V_{LED} + V_D) \times 1.2 \quad \textbf{Equation 18}$$

The drain current rating of the selected MOSFET should be greater than the value calculated from Equation 19 when the case temperature is at +70˚C. The MOSFET should be mounted on a board according to the manufacturer's specs in order to dissipate heat.

$$ID_{RMS} = \left(\sqrt{(IL_{AVG})^2 \times D_{MAX}}\right) \times 1.3 \quad \textbf{Equation 19}$$

MOSFET Q1 dissipates power due to both switching losses as well as conduction losses. The conduction losses can be calculated from Equation 20. R_{DSON} is the on-resistance of the MOSFET Q1 when the assumed junction temperature is +100˚C.

$$P_{COND} = (IL_{AVG})^2 \times D_{MAX} \times R_{DSON}$$ **Equation 20**

The switching losses of the MOSFET Q1 can be calculated with the use of Equation 21. IG_{ON} and IG_{OFF} are the gate currents of MOSFET Q1 when it is turned on and off. C_{GD} is the gate-to-drain MOSFET capacitance measured in farads.

$$P_{SW} = \left(\frac{IL_{AVG} \times V_{LED}{}^2 \times C_{GD} \times f_{SW}}{2} \right) \times \left(\frac{1}{IG_{ON}} + \frac{1}{IG_{OFF}} \right)$$ **Equation 21**

The MOSFET Q1 should be chosen so that it has a higher power rating than the value calculated from Equation 22 when the case temperature is +70˚C.

$$P_{TOT}(W) = P_{COND}(W) + P_{SW}(W)$$ **Equation 22**

The dimming MOSFET Q2 should be chosen such that the drain-to-source voltage rating is higher than V_{LED} by 20%. The continuous current rating at +70˚C should be higher than the LED current by 30%.

A Schottky diode should be used as the rectifier D1 for fast switching and to reduce the power dissipation. The selected diode should have a voltage rating 20% above the maximum converter output voltage. The maximum converter output voltage is V_{LED}. The current rating of the diode should be greater than I_D which can be calculated from Equation 23.

$$I_D = IL_{AVG} \times (1 - D_{MAX}) \times 1.5$$ **Equation 23**

The LED current control loop is made up of the switching converter, the LED current amplifier, and the error amplifier. The LED current control loop should be compensated for stable control of the LED current. The small-signal transfer function of the switching converter has a right half-plane (RHP) zero as the inductor current is in continuous conduction mode. A way to avoid this zero is to roll off the loop gain to 0dB at a frequency that is less than one fifth of the RHP zero frequency. The worst-case RHP zero frequency can be calculate from Equation 24.

$$f_{ZRHP} = \frac{V_{LED} \times (1 - D_{MAX})^2}{2\pi \times L \times I_{LED}}$$ **Equation 24**

The small-signal transfer function of the switching converter has an output pole which can be determined from the effective output impedance. The effective output impedance can be calculated with Equation 25. R_{LED} is the dynamic impedance of the LED string at the operating current. The dynamic impedance is the rate of change of voltage with current. The dynamic impedance of the LED can be calculated directly from the datasheet by drawing a line tangent to the Q-point of the I-V curve, and calculating its slope.

$$R_{OUT} = \frac{(R_{LED} + R10) \times V_{LED}}{(R_{LED} + R10) \times I_{LED} + V_{LED}} \qquad \textbf{Equation 25}$$

The output pole frequency which was mentioned above, can be found using Equation 26.

$$f_{P2} = \frac{1}{2\pi \times C_{OUT} \times R_{OUT}} \qquad \textbf{Equation 26}$$

R7 and C7 are the compensation components. C7 introduces a low-frequency pole which produces a -20dB/decade slope into the loop gain. R7 flattens the gain of the error amplifier for frequencies above the zero formed by R7 and C7. R7 fixes the total loop gain at f_{P2} such that the gain crosses 0dB at -20dB/decade at one-fifth of the RHP zero. GM_{COMP} is the transconductance of the error amplifier in Siemens.

$$R7 = \frac{f_{ZRHP} \times R8}{5 \times f_{P2} \times (1 - D_{MAX}) \times R10 \times 9.9 \times GM_{COMP}} \qquad \textbf{Equation 27}$$

$$C7 = \frac{1}{2\pi \times R7 \times f_{P2}} \qquad \textbf{Equation 28}$$

Experimental	R5	R10	R6	RT (R3 kΩ)	R8	R9	R1	R2	R4	R7
	2100	0.1	9112.121212	10	0.0689655	1000	30031.35889	13000	17815.33101	12.677

Actual	R5	R10	R6	RT (R3 kΩ)	R8	R9	R1	R2	R4	R7
	2100	0.1	9100	10000	0.07	1000	30000	13000	17800	13

Vov	Vuven	VREF	fosc	VLED	VD	VinMin	VFET	ILED	ΔVoutripple	ΔVin	Rled	Rdson	Cgd	Igon	Igoff	GMcomp
27	4.75	3.7	500000	14	0.7	4.75	0.2	0.7	0.15	0.15	0.485714286	0.058	50	4	5	5.00E-04

Dmax	Ilavg	ΔIL	ILP
0.686206897	2.2307692	1.3384615	2.9

Q1	Vds	ID(RMS)	Pcond	Psw	Ptot
	17.64	2.402290574	0.198057988	2459423077	2E+09

Output Cap	Cout	ESRcout	Icout(RMS)
Experimental	1.281E-05	0.0258621	1.03515142
Actual	1.50E-05		

Q2	fZRHP	Rout	fp2
	31342.7	0.047614563	2.23E+05

D1	Id
	1.05

Input Cap	Cin	ESRcin	Icin(RMS)
	4.462E-06	0.0560345	0.386380565

Experimental	L	C2	C7
	4.665E-06	2.317E-09	5.49E-08

Actual	L	C2	C7
	0.00001	2.40E-09	5.60E-08

FIGURE 8

COMPONENT VALUES SPREADSHEET

Figure 8 shows an excel file that was created in order to keep all the equations for finding the component values organized. This made it a lot easier to see what component values changed when some of the initial parameters had to be updated. Table 13 shows the Bill of Materials for the LED driver circuit. An extra set of parts was ordered as a backup just in case some of the parts malfunction, get lost, or get damaged in the process of soldering them to the board.

TABLE 13

BILL OF MATERIALS

Index	Description	Reference	Manufacturer	Supplier	Part Number	Quantity	Price	Total
1	CONN POWER JACK 2.1X5.5MM HI CUR	Vin	CUI Inc	Digikey	CP-002AHPJCT-ND	2	$1.89	$3.78
2	PWR SUPPLY WALL 5V 4A	Power	Triad Magnetics	Digikey	237-1420-ND	1	$14.42	$14.42
3	CONN HEADER 2POS R/A W/CLIP TIN		Molex Inc	Digikey	WM1870-ND	2	$0.99	$1.98
4	RES SMD 30K OHM 0.1% 1/10W 0603	R1	Panasonic Electonic Components	Digikey	P30KDBCT-ND	2	$0.63	$1.26
5	RES SMD 13K OHM 1% 1/10W 0402	R2	Panasonic Electonic Components	Digikey	P13.0KLCT-ND	2	$0.10	$0.20
6	RES SMD 10K OHM 1% 1/10W 0402	R3	Panasonic Electonic Components	Digikey	P10.0KLCT-ND	2	$0.10	$0.20
7	RES SMD 17.8K OHM 1% 1/10W 0402	R4	Panasonic Electonic Components	Digikey	P17.8KLCT-ND	2	$0.10	$0.20
8	RES SMD 2.1K OHM 1% 1/10W 0402	R5	Panasonic Electonic Components	Digikey	P2.10KLCT-ND	2	$0.10	$0.20
9	RES SMD 9.1K OHM 0.1% 1/10W 0603	R6	Panasonic Electonic Components	Digikey	P9.1KDBCT-ND	2	$0.63	$1.26
10	RES SMD 48.7 OHM 1% 1/10W 0603	R7	Panasonic Electonic Components	Digikey	P48.7HCT-ND	2	$0.10	$0.20
11	RES SMD 0.07 OHM 1% 3W 2512	R8	Bourns Inc	Digikey	CRA2512-FZ-R070ELFCT-ND	2	$0.60	$1.20
12	RES SMD 1K OHM 1% 1/10W 0603	R9	Panasonic Electonic Components	Digikey	P1.00KHCT-ND	2	$0.10	$0.20
13	RES SMD 0.1 OHM 1% 1/10W 0603	R10	Panasonic Electonic Components	Digikey	P.10AJCT-ND	2	$0.48	$0.96
14	DIODE SCHOTTKY 40V 2A DO220AA	D1	Vishay Semiconductor Diodes Division	Digikey	SS2P4-M3/84AGICT-ND	2	$0.40	$0.80
15	MOSFET N-CH 40V 3A SOT23-3	Q1&Q2	Vishay Siliconix	Digikey	SI2318DS-T1-E3CT-ND	4	$0.56	$2.24
16	CAP CER 6.8UF 16V 10% X7R 1206	Cin	TDK Corporation	Digikey	445-4040-1-ND	2	$0.45	$0.90
17	CAP CER 2400PF 50V 5% NP0 0603	C2	Murata Electronics North America	Digikey	490-3282-1-ND	2	$0.16	$0.32
18	CAP CER 15UF 6.3V 20% X5R 0603	Cout	TDK Corporation	Digikey	445-8027-1-ND	2	$0.41	$0.82
19	CAP CER 0.15UF 25V 10% X7R 0603	C4	TDK Corporation	Digikey	445-5190-1-ND	2	$0.10	$0.20
20	CAP CER 2.2UF 10V 10% X5R 0603	C5	TDK Corporation	Digikey	445-5166-1-ND	2	$0.18	$0.36
21	CAP CER 0.47UF 6.3V 10% X5R 0402	C6	TDK Corporation	Digikey	445-4996-1-ND	2	$0.10	$0.20
22	CAP CER 0.22UF 16V 10% X7R 0603	C7&C8	TDK Corporation	Digikey	445-1318-1-ND	4	$0.10	$0.40
23	CAP CER 220UF 6.3V 20% X5R 1210	C9	Samsung Electro-Mechanics America Inc	Digikey	1276-3375-1-ND	2	$1.65	$3.30
24	FIXED IND 10UH 7.2A 16.3 MOHM	L1	Wurth Electronics Inc	Digikey	732-4179-1-ND	2	$4.56	$9.12
25	IC LED Driver DC DC Controller Analog	X1	Maxim Integrated	Digikey	MAX16834ATP+-ND	2	$6.59	$13.18
26	BOARD LED IMS CREE X-LAMP	X-RE PCB	Bergquist	Digikey	BER272-ND	4	$1.01	$4.04
27	STARBOARD HEATSINK 4.33C/W 0.5"		Wakefield-Vette	Digikey	345-1104-ND	4	$2.58	$10.32
28	STAR BOARD THERMAL INTERFACE PAD		t-Global Technology	Digikey	1168-1715-ND	4	$0.25	$1.00
29	TEST POINT PC MINI .040"D BLACK		Keystone Electronics	Digikey	5001K-ND	10	$0.36	$3.60
30	CONN HEADER VERT SGL 2POS GOLD		3M	Digikey	3M9447-ND	10	$0.16	$1.60
31	CONN JUMPER SHORTING .100" GOLD		Sullins Connector Solutions	Digikey	S9337-ND	4	$0.13	$0.52
							Sutbtotal	$78.98

Once the component values are obtained for the driver, the next step is to simulate it. The following section outlines the steps needed in order to create a model for the Cree XR-E LED so that the driver can be simulated.

VI. CREATING LED PSPICE MODEL

In order to create a simulation for the LED driver, I needed to obtain a model for the Cree XR-E LED. I was able to find the model for an Xlamp ML-E which is another type of LED produced by Cree. After looking at the file and doing some research I found out that I just needed to change the IS, N, and RS parameters shown in Figure 9 to closely match those of the XR-E LED in order to obtain the same IV characteristics as those found in the datasheet which is shown in Figure 10. In order to find the saturation current (IS) and the emission coefficient (N), I had to obtain as many points as possible from the IV curve in Figure 10 and plot them in excel. An application for Google Chrome called WebPlotDigitizer was used to find as many points on the curve as possible with very high accuracy. A screenshot was first taken of the IV curve and cropped and saved as a jpeg file. It was then loaded into the application by selecting load image under the File setting on the top left corner of the screen as shown in Figure 11. Once the image is selected, the next step was to click on 2D(X-Y) Plot and click on align axis as shown in Figure 12.

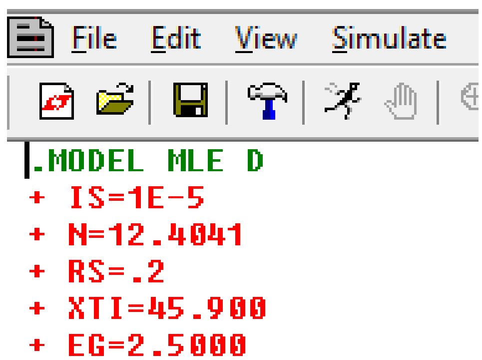

FIGURE 9

GENERIC PSPICE LED MODEL

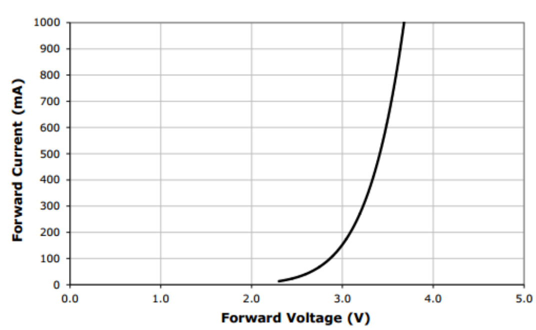

FIGURE 10

ELECTRICAL CHARACTERISTICS OF XR-E LED (TJ = 25 ˚C)

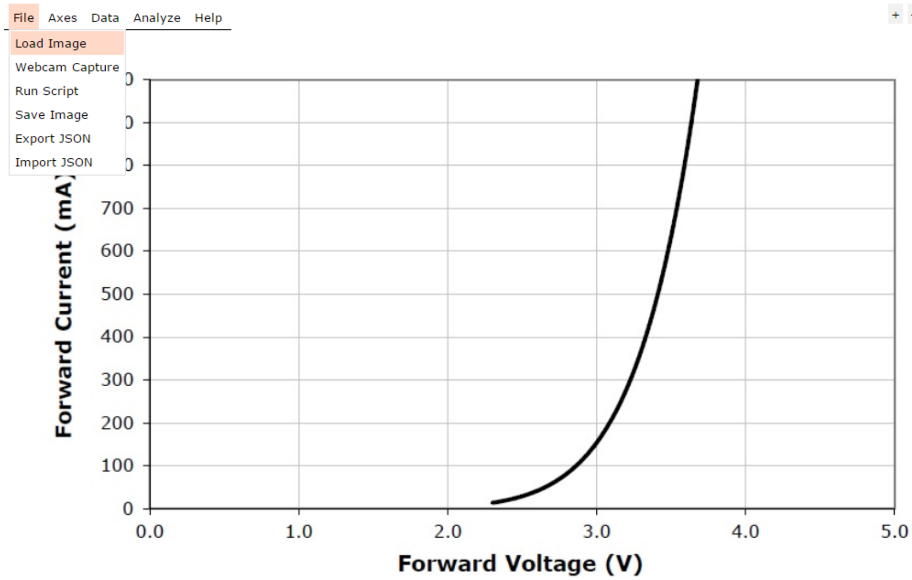

FIGURE 11

LOADING IMAGE INTO WEBPLOTDIGITIZER

The next screen shown in Figure 13 asks the user to select 4 known points on the plot in the order that is shown in the image. The points are chosen as shown in Figure 14 and then the Complete button is clicked. This brings up the screen shwon in Figure 15 which asks for the values of the points that were just entered. The next screen asks the user to select the data points which they would like to be read from the graph. This can be done either manually by clicking anywhere along the line leaving behind small red dots as shown in Figure 16 or through automatic mode.

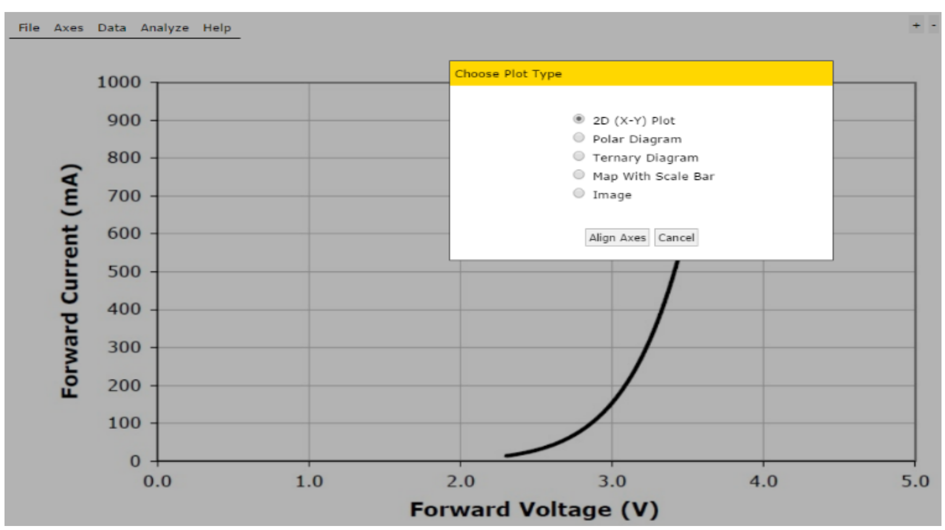

FIGURE 12

SELECTING PLOT TYPE

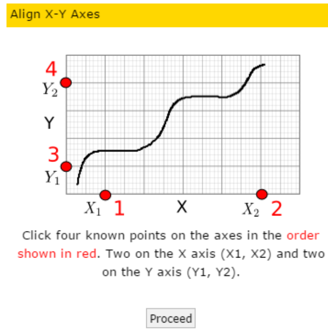

FIGURE 13

ALIGNING X-Y AXES

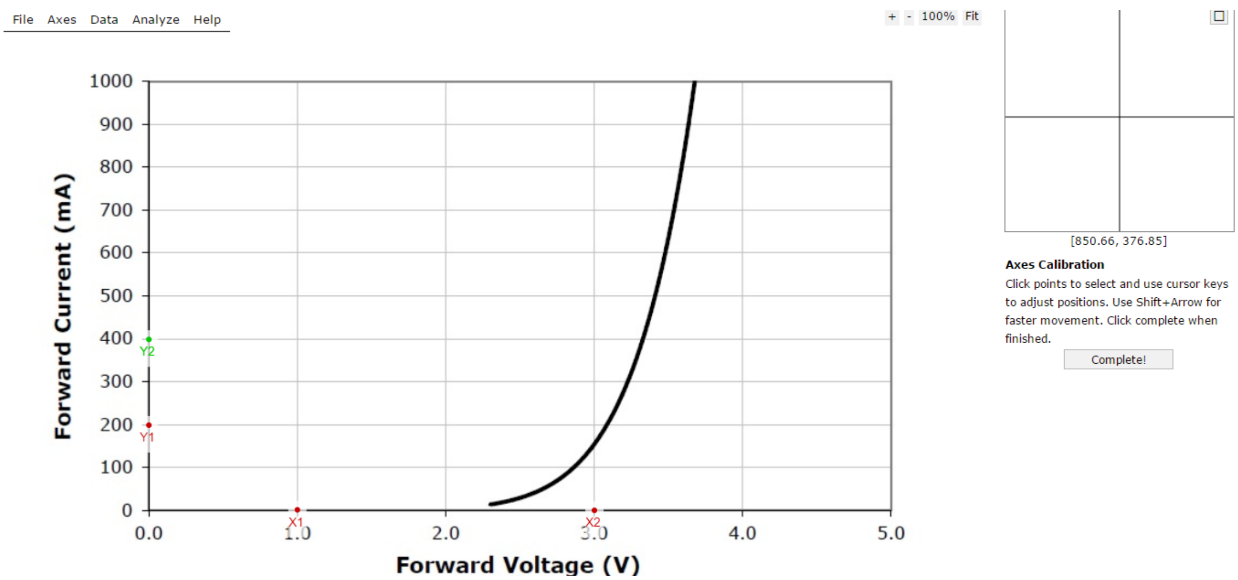

FIGURE 14

CALIBRATING AXES

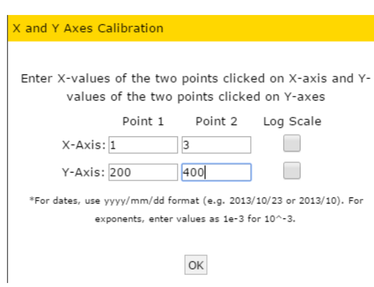

FIGURE 15

X-Y AXES VALUES

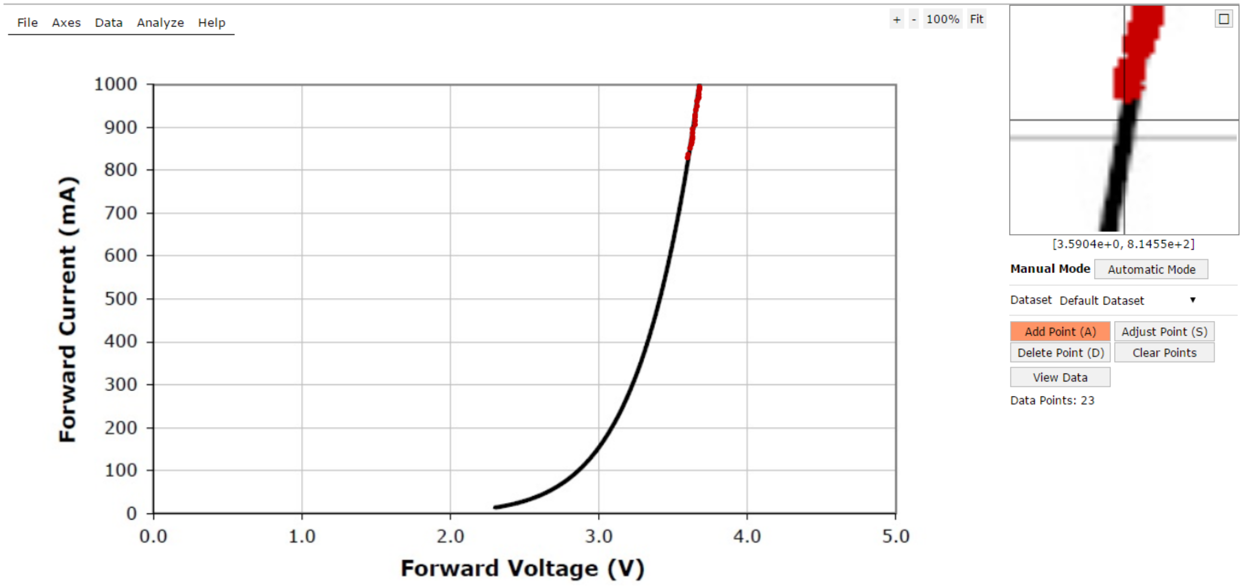

FIGURE 16

SELECTING DATA POINTS

The next step was to click on view data and download all the acquired data as a CSV file. The file can then be opened in excel and plotted as shown in Figure 17. An exponential fit trendline is added to the plot to obtain the value for the saturation current and the emission coefficient.

The saturation current is the value shown underlined in red in Figure 17. The emission coefficient is found by using an equation that is set equal to the value underlined in blue and solving for N. The SPICE model for the LED matches that of the diode equation shown below. The underlined portion shown in blue is set equal to the power which e is raised to in the equation shown below. Since all the values needed for the model to behave as the Cree XR-E LED have been found, all that is needed is to go back to the model file shown in Figure 9 and to enter the new values for IS, N, and RS. Section VII explains how to enter the model files into the circuit simulation software.

$$If = IS * (e^{\frac{Vf}{N*Vt}} - 1)$$

$$3.1007Vf = \frac{Vf}{N * Vt}$$

$$3.1007 = \frac{1}{N * 0.026}$$

$$\boldsymbol{N = 12.4041}$$

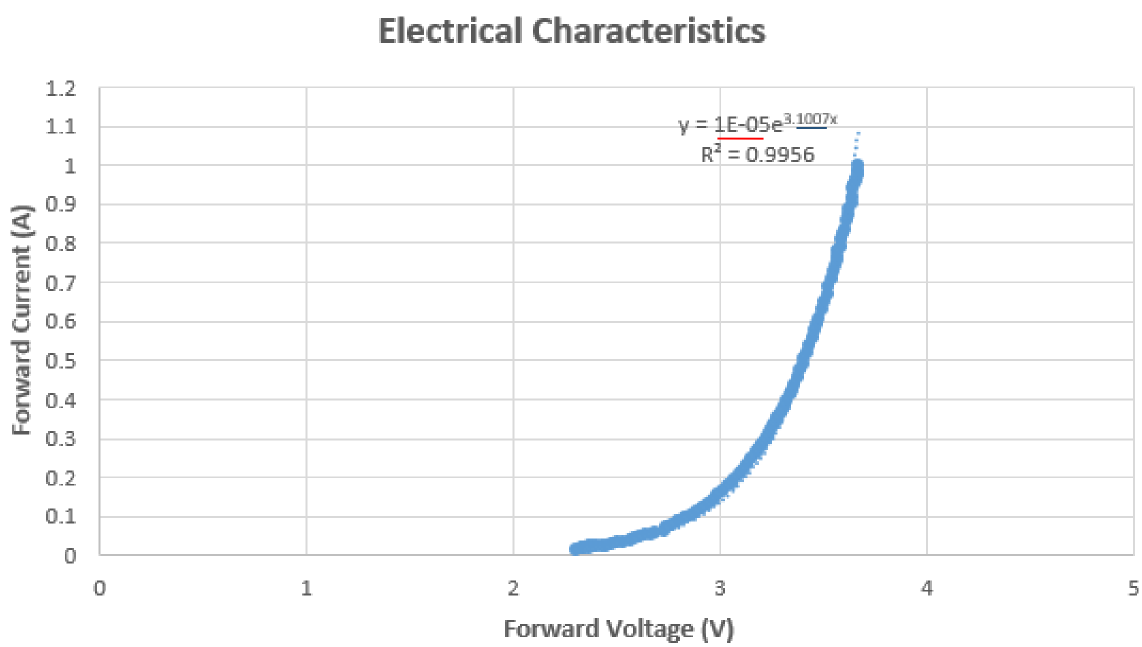

FIGURE 17
EXCEL ELECTRICAL CHARACTERISTICS PLOT

VII. IMPORTING MODEL FILES TO PSPICE

Once all the model files for the components are obtained, the next step is to export them into model files that can be used by OrCAD Capture in order to be able to layout the circuit. The library files can only be opened one at a time in the Model Editor. The library file for the MAX16834 integrated circuit once loaded into the Model Editor can be seen in Figure 18.

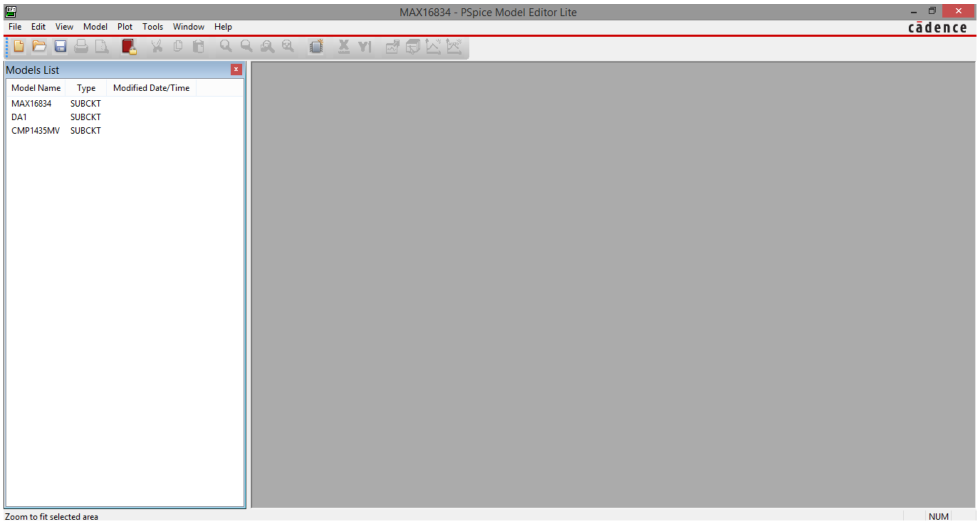

FIGURE 18

PSPICE MODEL EDITOR

Once the file is opened in the Model Editor, the next step is to go under File and select Export to Capture Part Library as shown in Figure 19. This brings up a new window which asks where to save the output file which has an .olb extension. The new file needs to be added to the library folder which can be found at OrCAD\OrCAD_16.6_Lite\tools\capture\library. The component can now be added in PSpice by clicking on Place and clicking on Part, the library file can be selected by clicking on the button shown in Figure 20 and then the desired component can now be added to the schematic. Once all the models are added to PSpice, a simulation can finally be ran and the results are shown in the next section.

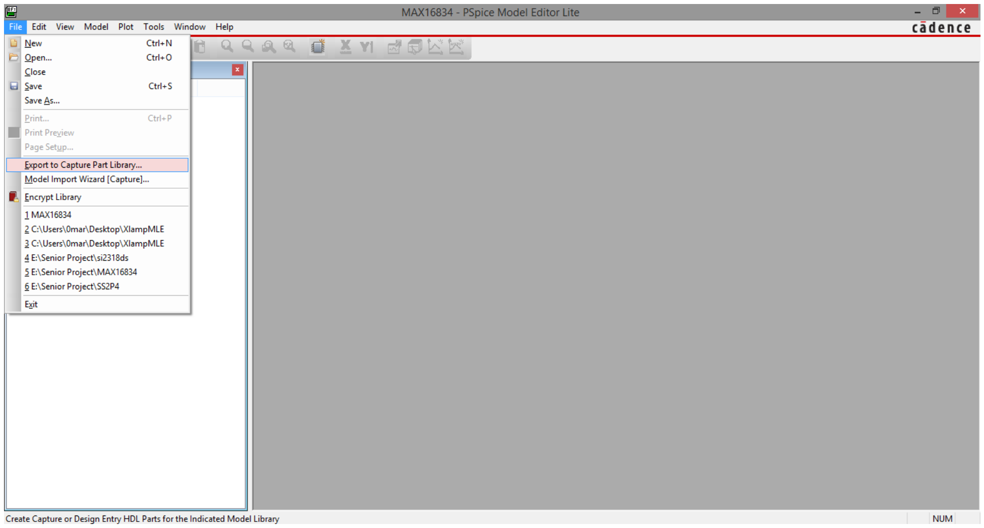

FIGURE 19

EXPORT WINDOW

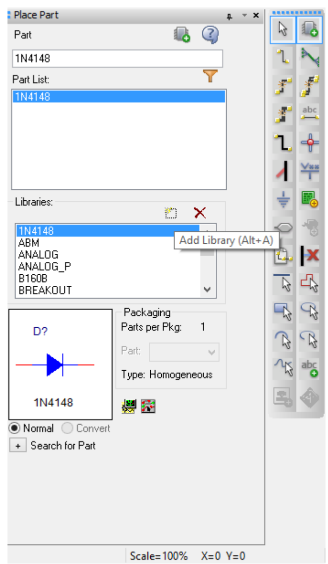

FIGURE 20

ADDING LIBRARY FILE

VIII. SIMULATION RESULTS

Figure 21 shows the completed Pspice schematic for the LED driver circuit. Initially when the simulation was running without a problem, there was a slight current and voltage spike that ran for about 3ms as shown in Figure 22. The rise in current could significantly decrease the performance of the LEDs even if it was just for a short period of time. A Metal Oxide Varistor or Transient Voltage Suppressors could reduce the sudden rise in current. A capacitor in parallel with the load could also help reduce the rise in current. Capacitor C9 was added in parallel to decrease the sudden rise in current and to prevent damage to the LEDs. The values shown in the schematic are the nominal values of the components, not the actual measured values.

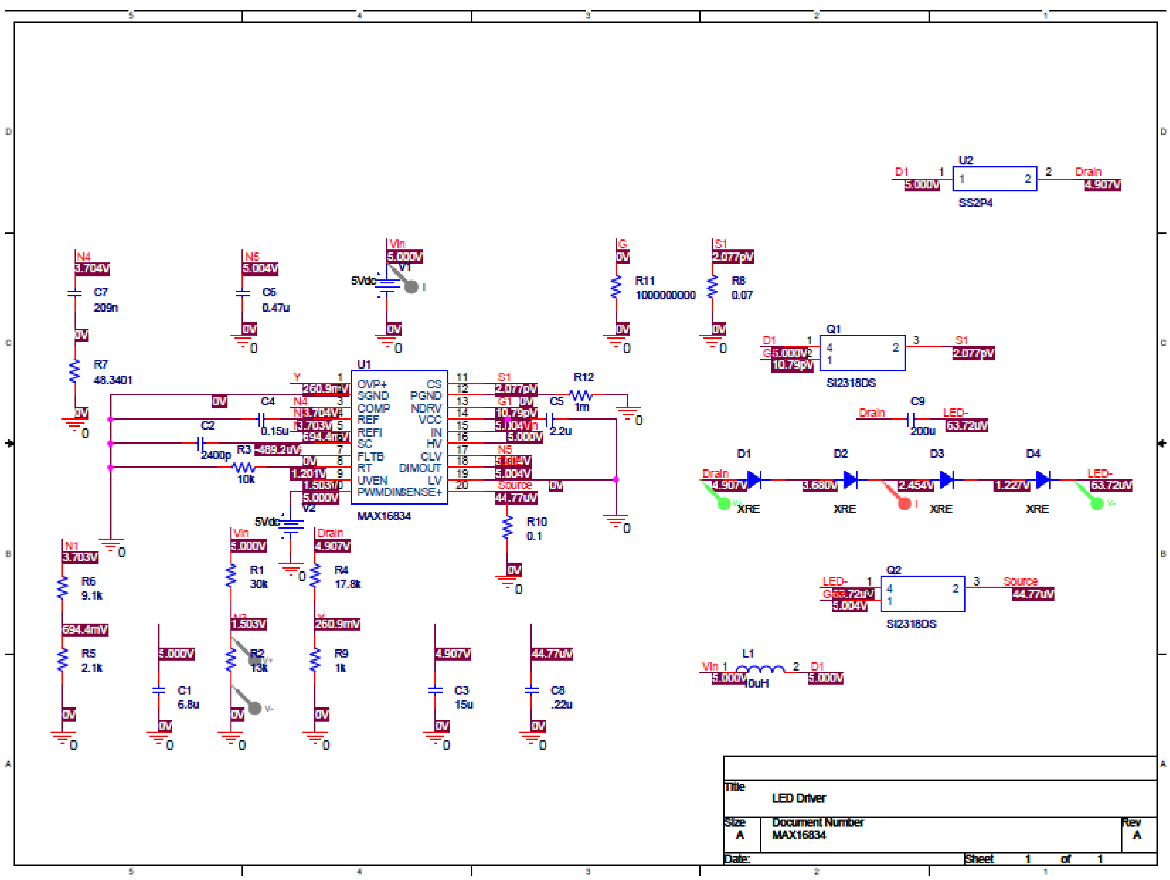

FIGURE 21

LED DRIVER PSPICE SCHEMATIC

Capacitor C9 was calculated by using the following equation:

$$i = C\,\frac{dV}{dt} \qquad \rightarrow \qquad C = 1A\,\frac{3ms}{15V}$$

The current rose to an amp and the voltage rose to about 15V, the time that the sudden rise occurred at was for about three milliseconds. These parameters were entered into the above equation and a capacitor value of about 200µF was obtained.

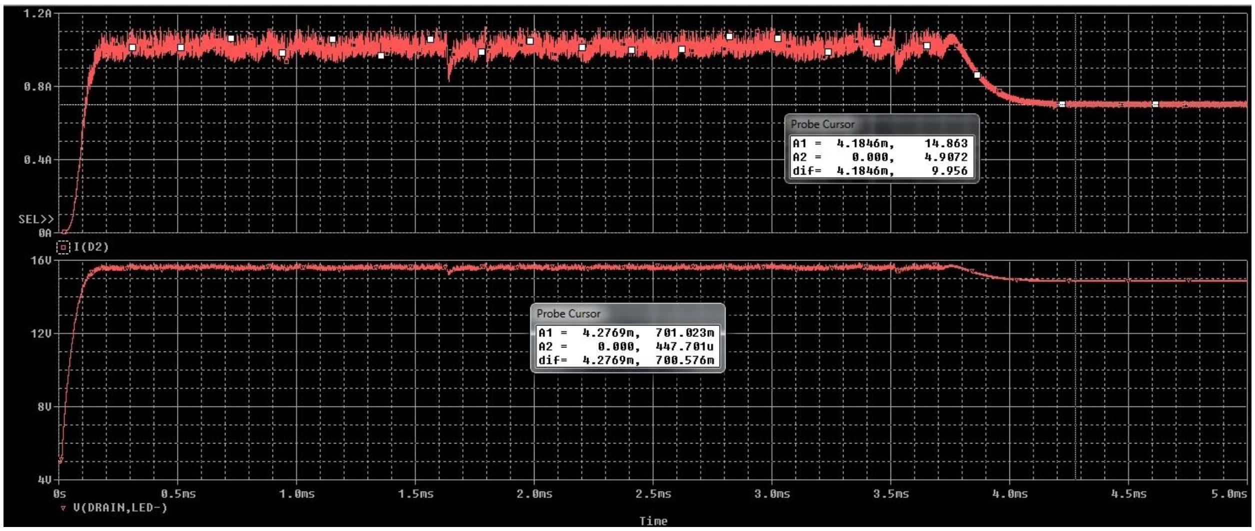

FIGURE 22

INITIAL PSPICE SIMULATION

The value for C9 was then added to the schematic and the simulation was run again to check the results. Figure 23 shows the new output voltage and current without the sudden initial peaks.

Some problems encountered during the design process of the LED driver are that the dynamic impedance of the LED string was not given in the datasheet. The dynamic impedance is used to find the effective output impedance of the driver which is then used to calculate the output pole frequency. The output pole frequency can then be used to calculate R7 and C7. In order to find the dynamic impedance, a line tangent to the Q-point had to be drawn on the IV curve of the LED shown in Figure 10. The slope was then calculated and multiplied by four to obtain the dynamic impedance of the whole string of LEDs. Another problem is that the output of the driver was too low, the output would show the current as being in Pico amps which

suggested that the driver was off. The problem was that the PWMDIM pin was connected to ground, the datasheet specifies that the pin has to be higher than 1.435V in order for the dimming MOSFET to turn on. The problem was solved by tying PWMDIM to the input voltage which is set at 5V. Another problem that was encountered after PWMDIM was tied to Vin is that the simulation was having convergence problems. After consulting Introduction to PSpice Using OrCAD for Circuits and Electronics by Muhammad H. Rashid, it was determined that RELTOL had to be changed to 0.01 and ITL4 had to be changed to 50 under Options in the Simulation Settings. After these changes the simulation was finally able to run and produced the plot shown in Figure 22. The PSpice model files and the Netlist for the LED Driver can be found in Appendix B. Once the simulation is running, the next step is to design a board that holds all the components in place. The design of the printed circuit board is outlined in the next section.

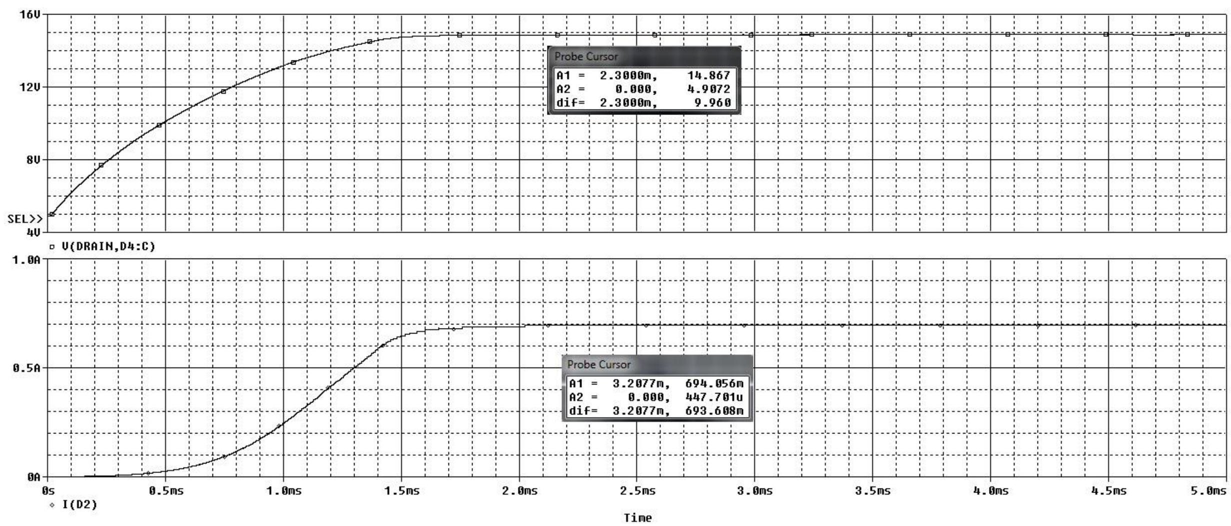

FIGURE 23

FINAL PSPICE SIMULATION

IX. BOARD DESIGN

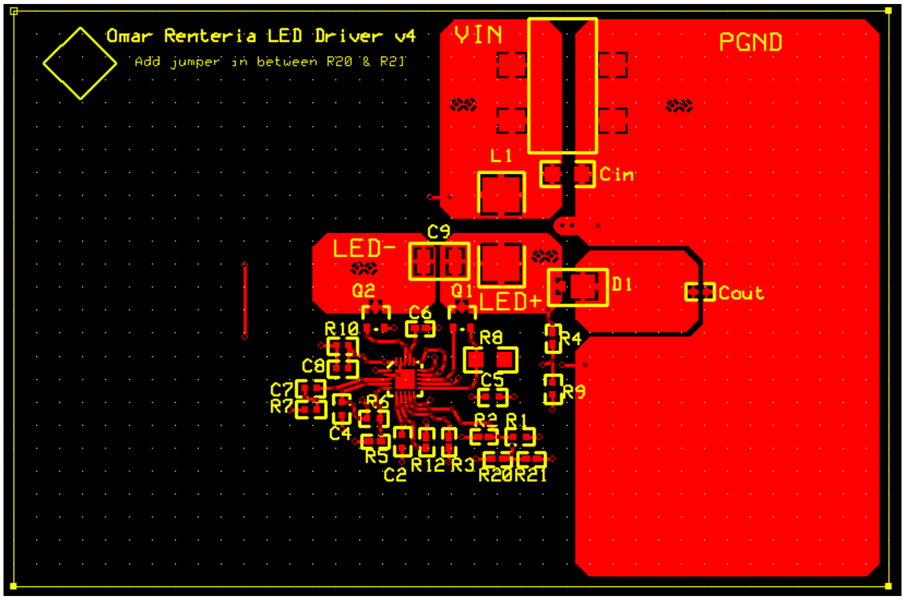

FIGURE 24
BOARD LAYOUT (TOP LAYER)

Figure 25 shows the finished schematic for the PCB which is done in ExpressPCB. The schematic is linked up to the PCB layout shown in Figure 24 to help during the routing of the traces. The circuit board for this project will be a 4-layer board that includes the solder masks and the silkscreen. The solder mask is a thin layer of material added to the top of the board to protect the copper traces against oxidation. The silkscreen is a layer added to the solder side of the board to identify the components, company logos or the board’s part number. The exact dimensions of this board are 3.8” x 2.5”. When a particular pin is clicked on the layout, its destination is highlighted in blue to help the designer locate it more efficiently. Figure 24 shows the top layer of the board as of now, very few changes need to be made to it in order to get a final working version. One of the changes is to make the trace widths ticker in certain areas depending on how much current they carry. Another change is to add a large copper plane to the bottom layer of the board which is shown in Figure 28 to act as heat sink for the exposed pad of the MAX16834 chip.

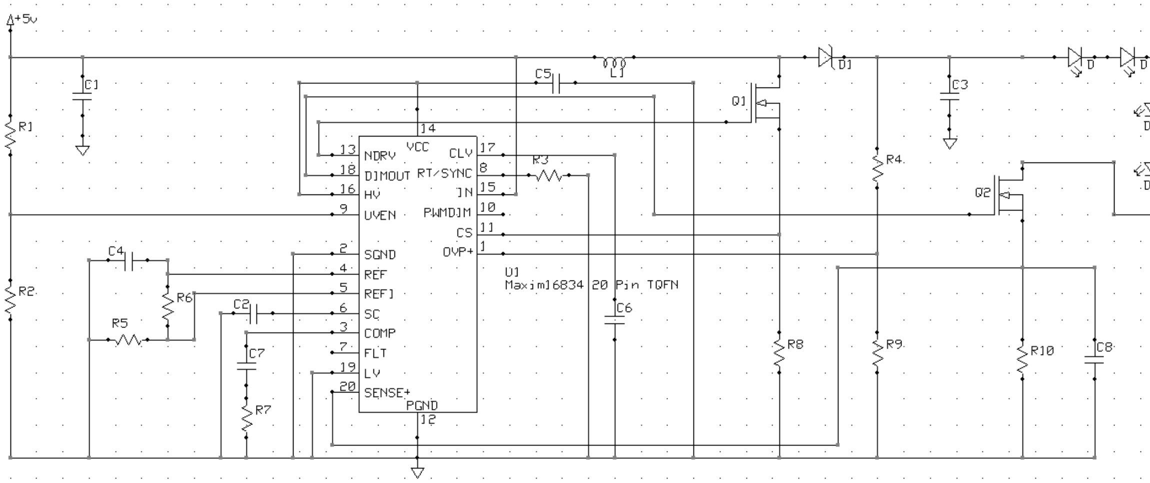

FIGURE 25
PCB SCHEMATIC

Figure 26 shows the ground layer of the board, the top portion which is separated by the dark lines is the power ground while the smaller area located at the bottom is the signal ground. The signal and power ground come together at a location which is very close to the MAX16834 chip. Figure 27 is the power layer of the board, it will not be used in this design so most of the copper is eliminated from the middle of the board to prevent a short.

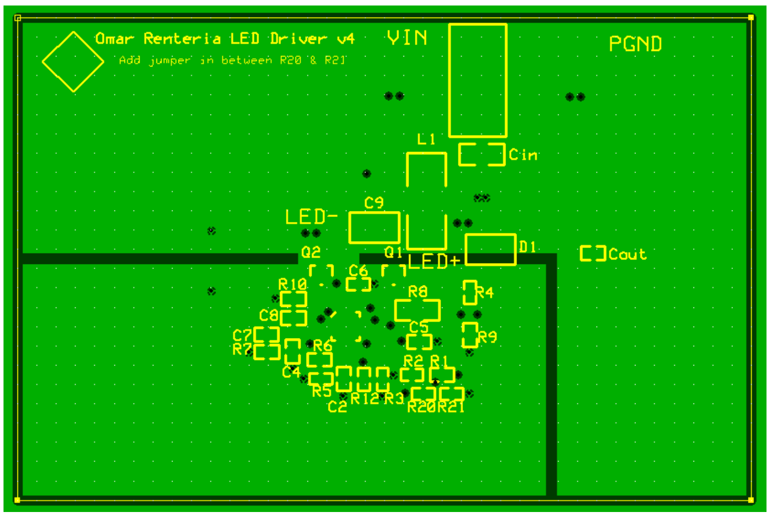

FIGURE 26
BOARD LAYOUT (GND LAYER)

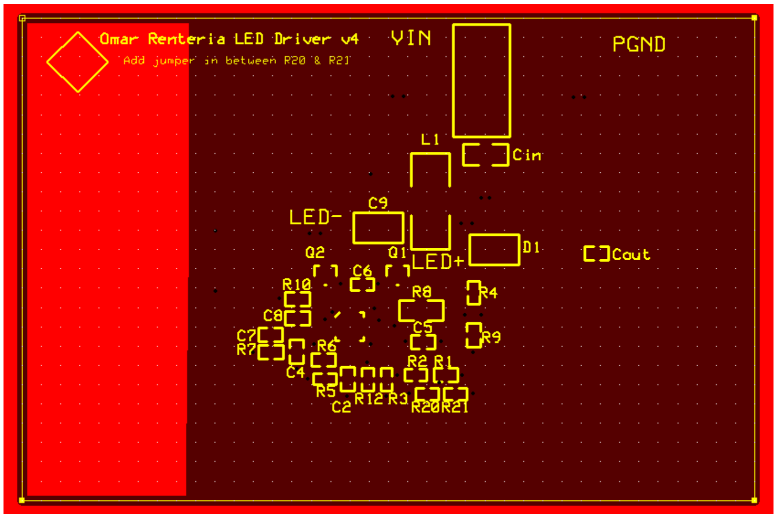

FIGURE 27
BOARD LAYOUT (POWER LAYER)

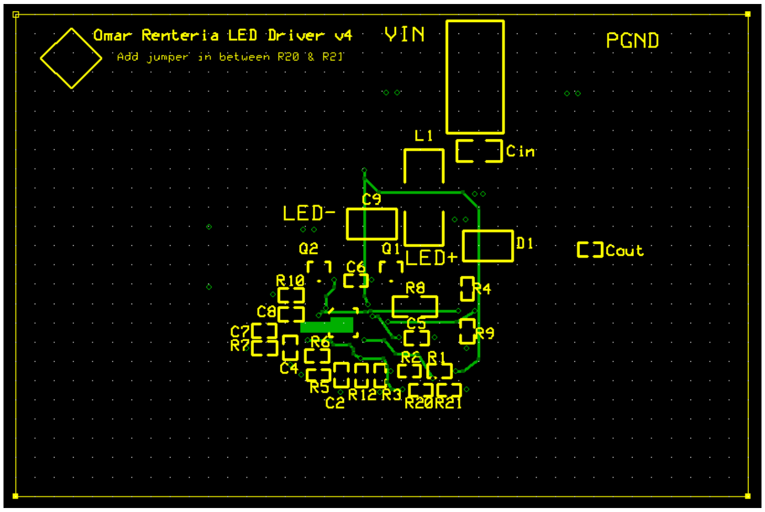

FIGURE 28
BOARD LAYOUT (BOTTOM LAYER)

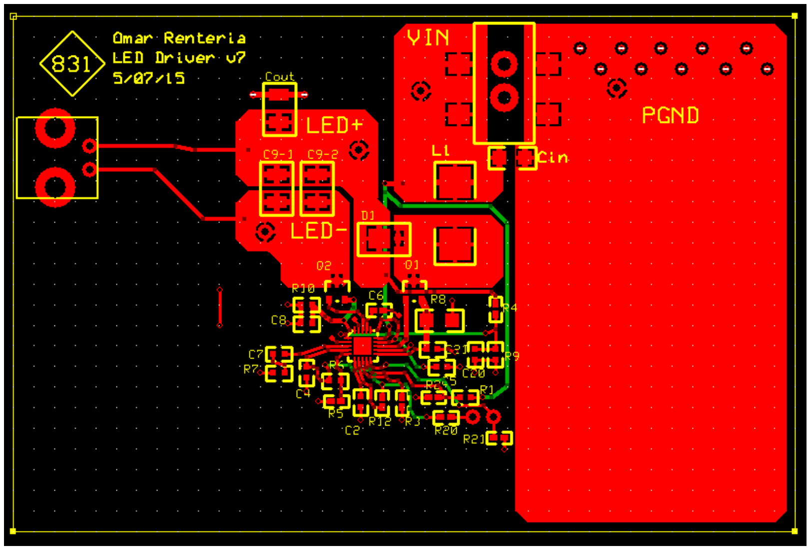

FIGURE 29

FINAL BOARD LAYOUT (TOP & BOTTOM LAYER)

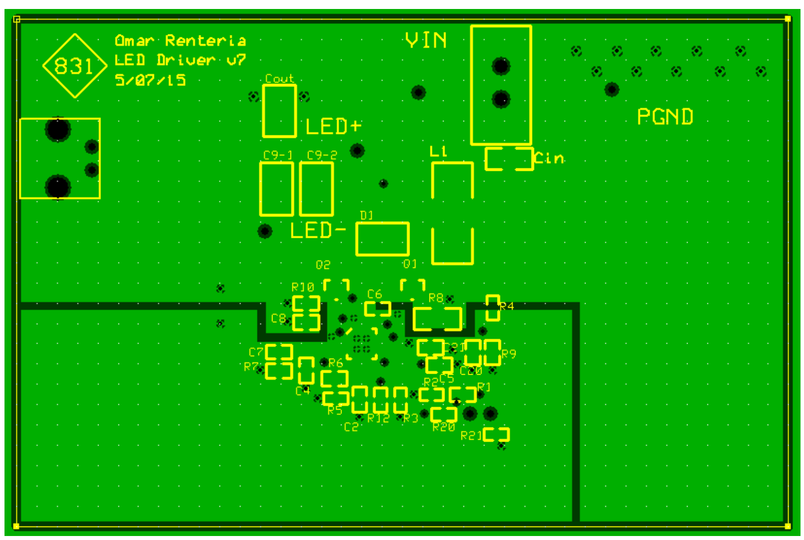

FIGURE 30

FINAL BOARD LAYOUT (GND LAYER)

Figure 29 shows the final layout of the board, it shows both the top and bottom layers of the board. There were a few major and minor changes to the board. One of the biggest changes was that the 4th revision shown in Figure 24 shows the output of the circuit which is labeled as LED+ is tied to the output of the inductor, this is completely wrong. Looking back at the schematic of the LED driver in Figure 7, it is shown that the output of the inductor is connected to the anode of the diode and the cathode is the one that is tied to LED+. The LED+ pad had to be moved closer to the LED- pad in order to add the two bypass capacitors labeled as C9-1 and

C9-2 between them. The two capacitors are added in order to prevent high current spikes from damaging the LEDs upon powering up the circuit. Another change is that a Molex connector is added to the left side of the board in order to allow the LEDs to be easily disconnected from the board. Another minor change is that test points were added to the board in order to allow connections to be made directly to the board for testing purposes. The copper plane located directly under the IC on the bottom layer of the board shown in Figure 28 was removed, instead 4 thermal vias were added to the exposed pad of the IC which are connected to the ground plane to provide a larger area for heat dissipation. Several vias are also added connecting PGND to the 2nd layer which is the GND layer shown in Figure 30. Another change is that two vias are added in between resistors 20 and 21 to connect a male header in between them. This is done in order so that a jumper can be added to the male header in order to power on the chip by adding an active high signal directly from the chip or so that an external PWM signal can be connected in order to control the brightness of the LEDs.

Figure 30 shows the ground layer of the circuit board. The lines separating the signal ground from the power ground are rearranged so that some of the signals from the components don't have to travel far.

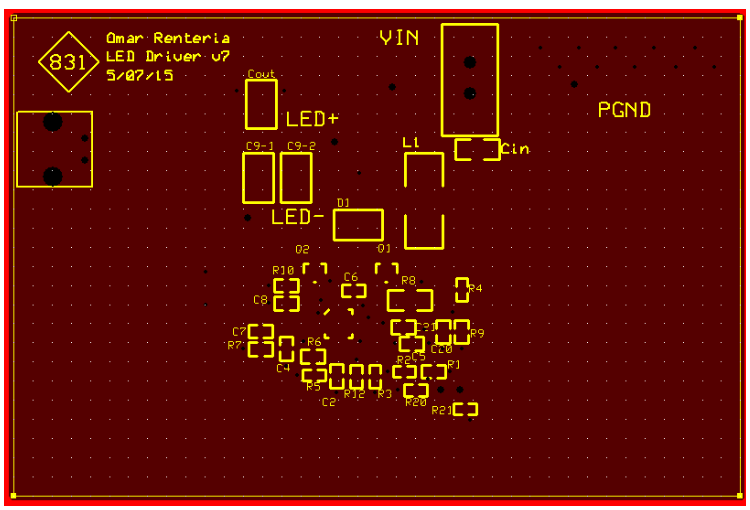

FIGURE 31
FINAL BOARD LAYOUT (POWER LAYER)

The power layer shown in Figure 31 was mostly the same, the only difference from the previous version which is shown in Figure 27 is that all the copper was removed in order to prevent shorts between the other layers of the board when vias are added connecting separate layers together. The next section outlines the process through which the heatsinks are chosen so that the LEDs operate well beneath their junction temperature.

X. HEAT SINK CALCULATIONS

Most of the electricity in an LED turns into heat rather than light. About 70% of the electricity is converted into heat while the remaining 30% is turned into light. If the heat is not removed, then the LED can run at very high temperatures and possibly have its efficiency reduced or maybe even stop working. Mostly all the heat in an LED is generated at the PN junction by electrical energy that was not converted into light. One way to reduce the junction temperature is through the use of a heat sink which helps dissipate the heat from the junction to the solder point, and from the solder point to the board, the board then transfers the heat to the heat sink. In order to determine what type of heat sink I need, I first had to find out of the thermal resistance of the heat sink that will help keep the junction temperature of the LED under the required amount. Figure 32 shows the thermal model of an LED, Tj is the junction temperature and Ta is the ambient temperature.

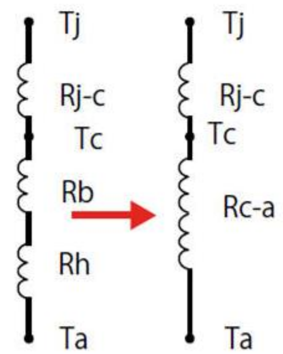

FIGURE 32
THERMAL MODEL OF AN LED

The junction temperature of the Cree XR-E LED is determined to be a maximum of 150˚C from the datasheet. Since I never want to reach the maximum junction temperature of the LED, I will use a much smaller value of 60˚C for calculation purposes. The forward current of each LED is 700mA and the forward voltage is 3.5V which are both obtained from the datasheet. The total power dissipated by the LED is 2.45W which is calculated by multiplying the forward voltage by the forward current. The ambient temperature is 25˚C and the thermal resistance Rj-c of the LED is 8˚C/W. The thermal resistance of the thermal pad is 1˚C/W which is obtained from the datasheet. The following calculations show how the thermal resistance of the heat sink is calculated.

$$Tc = Tj - (Rj - c * Pd)$$

$$Tc = 60 - (8 * 2.45)$$

$$Tc = \mathbf{40.4^{\circ}C}$$

$$Tb = Tc - (Rb * Pd)$$

$$Tb = 40.4 - (1 * 2.45)$$

$$Tb = \mathbf{37.95^{\circ}C}$$

$$Rh = (Tb - Ta)/Pd$$

$$Rh = (37.95 - 25)/2.45$$

$$Rh = \mathbf{5.29^{\circ}C/W}$$

The thermal resistance of the heat sink required is calculated to be 5.29˚C/W, a heat sink with a thermal resistance less than the calculated value needs to be picked. I decided to go with the Wakefield-Vette 882-50AB heat sink which has a thermal resistance of 4.33˚C/W.

FIGURE 33
HEAT SINK & HARDWARE

Figure 33 shows the Wakefield-Vette heat sink that will be used for the Cree XR-E LEDs on the far right. The star board on which the LED is mounted on is located in the middle and the thermal pad which secures the star board to the heat sink is shown in the far left. The star board will also be secured to the heat sink with the help of six 4-40 screws.

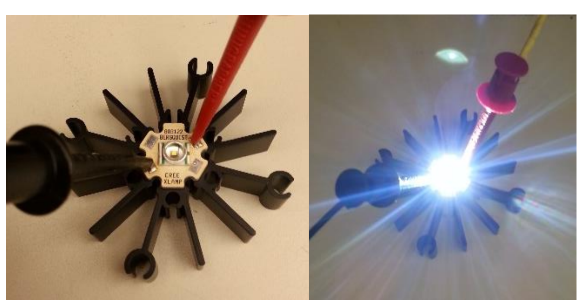

FIGURE 34
LED MOUNTED ON HEAT SINK

Figure 34 shows the star board with the LED mounted on the heat sink on the left, and it shows the LED while it is being supplied approximately 3.3V at 700mA on the right. Figure 35 shows that the LED is being powered by around 2.303W while being supplied with 3.3V at 700mA.

FIGURE 35
POWER BEING SUPPLIED TO LED

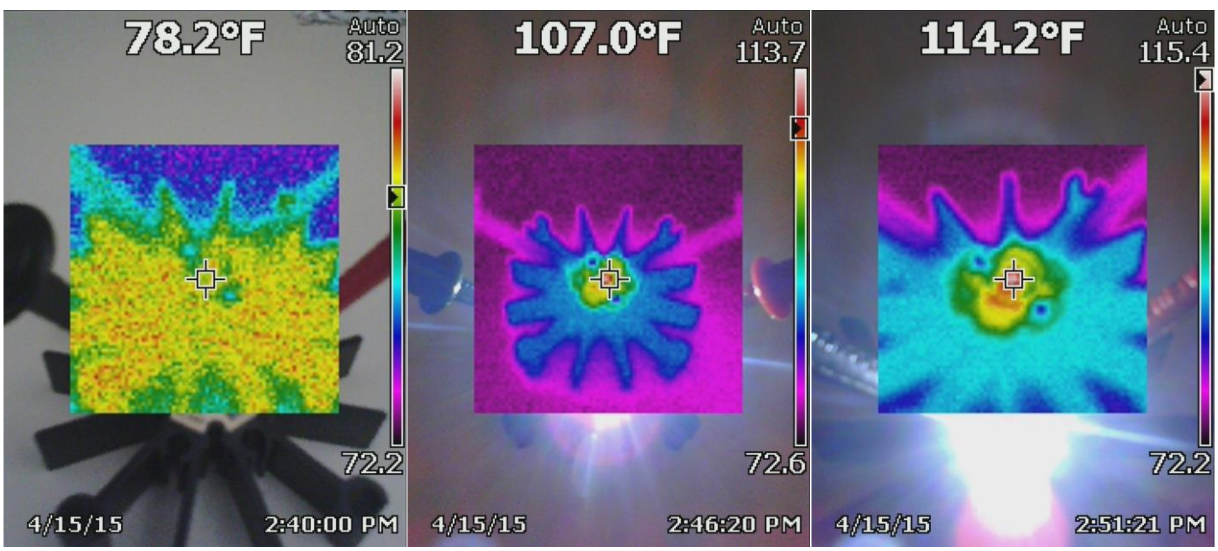

FIGURE 36
THERMAL IMAGES OF LED

Figure 36 shows some thermal images of the LED taken with a Fluke Ti95 Thermal Imager. The picture to the left was taken right before powering the LED which and it was at room temperature. The middle picture shows the whole heat sink and LED when it is being powered by approximately 3.3V at 700mA. The picture located on the right shows a close up of the LED and it shows that the surface of the LED is operating at approximately 114˚F. These temperatures do not represent the junction temperature of the LED. In order to find the junction temperature of the LED I will need to use a thermocouple at the designated spot shown in Figure 37. A thermocouple is made of two thin metal wires that are composed of two different types of metal. The ends of the two wires are welded together and the leads are separated with insulation so that only the welded portion is in contact with the test point. Once the welded point is heated or cooled, it creates a DC voltage differential between the two metals. The voltage is then converted into a temperature reading by a thermometer.

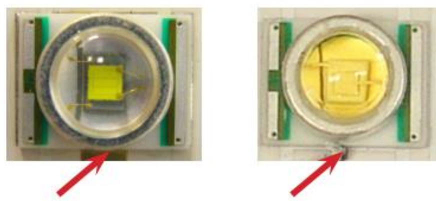

FIGURE 37
THERMOCOUPLE LOCATION

Thermocouple types are determined according to the type of metals from which they are made. Figure 38 shows a model for a type k thermocouple which is composed of Nickel-Chromium for the +lead and Nickel-Aluminum for the –lead.

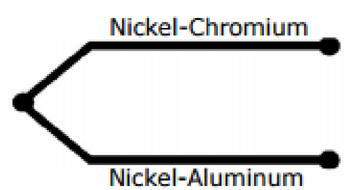

FIGURE 38
TYPE K THERMOCOUPLE

Once the solder-point temperature is measured with the thermocouple, the following equation can be used to determine the junction temperature of the LED. T_{sp} is the solder-point temperature, θ_{th} is the thermal resistance of the LED, and P_{total} is the total power input to the LED.

$$T_j = T_{sp} + \theta_{th} * P_{total}$$

XI. MICROCONTROLLER

The MAX16834 offers a dimming input which can be used for pulse-width modulating the output current. PWM dimming can be achieved by driving the PWMDIM pin with a pulsating voltage source. Pulse-width modulation can be implemented using a microcontroller. I will be looking into producing a PWM signal with a microcontroller and varying its duty cycle to control the dimming input of the MAX16834. I will be using the Microduino-Core+ which is about the size of a quarter and it is compatible with the Arduino development environment. The varying duty cycle can be achieved through the use of a potentiometer and coding through the Arduino development environment. A picture of the Microduino can be seen in Figure 39.

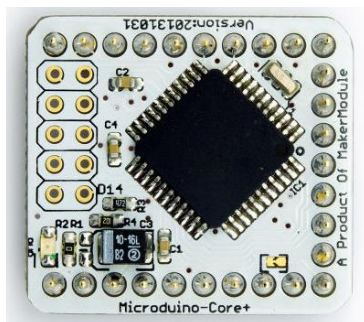

FIGURE 39
MICRODUINO-CORE+

XII. ASSEMBLY

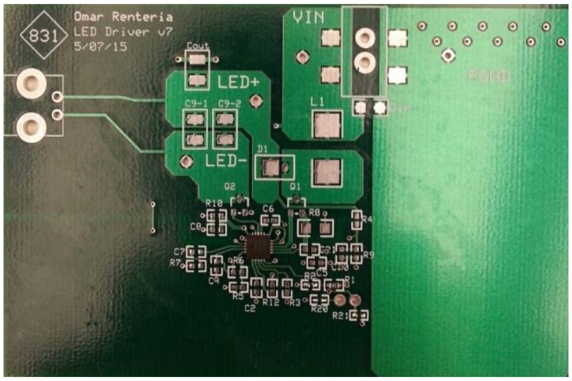

FIGURE 40

MANUFACTURED CIRCUIT BOARD

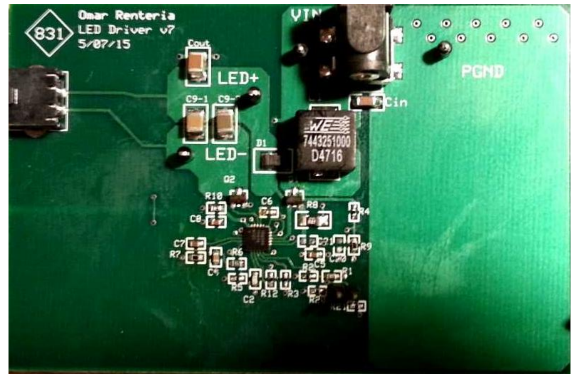

FIGURE 41

FINISHED CIRCUIT BOARD

Figure 40 shows the final version of the printed circuit board once I received it from the fabrication house. The IC shown in the middle was soldered on campus with the use of a reflow oven. The temperature profile of the solder was obtained from the datasheet and was programmed into the reflow oven so that it would melt and flow smoothly across the solder pad. The big components such as the DC connector, inductor, Molex connector, and test points were soldered with a soldering iron. The smaller components were soldered on with the help of a hot-air rework station such as the one pictured in Figure 42. Thermal paste was added to each pad and the small components where placed with the use of fine tip ESD safe tweezers onto each pad. The hot-air gun was then carefully used to heat the solder and wait until the surface tension of the solder aligns the component in the pads. After each component was soldered, I verified with a multimeter that it was making a solid connection with the pads. The four LEDs connected in series that will be powered by the driver are shown in Figure 43. The LEDs are mounted onto the starboard with the help of the hot-air gun since the pads are located underneath the LED and are then mounted on the heat sink with the thermal pads shown in Figure 33. After soldering the components, the next step was to test the board. The testing process is outlined in section XIII.

FIGURE 42

AOYUE 2703A+ HOT-AIR REWORK STATION

FIGURE 43

LEDS CONNECTED IN SERIES

XIII. TESTING

Unfortunately, the junction temperature of the LED was not able to be measured. The multimeter which included a thermocouple that was available for use in the power lab was not functioning. Upon inspection, I found out that the batteries corroded inside of the multimeter and damaged the tabs that provide power from the battery to the circuitry therefore rendering it useless. The internal components could have also possibly been damaged if some of the solution found inside of the battery made its way to the inside of the multimeter. A Fluke Ti95 Thermal Imager was used instead to check the external temperature of the LED, this does not provide a measurement of the junction temperature but it provided me with an actual measurement of temperature at which the LEDs were operating in. The LEDs were then connected to a power supply to briefly supply power to them to make sure that they were functioning properly before being connected to the driver. As previously mentioned, every component was checked with a multimeter after it was soldered to make sure that it made contact with the pads. The resistance of each resistor was also measured after being soldered to make sure that it was the right value. The last step before connecting the supply to the DC power jack was to verify its polarization. The datasheet indicated that the power jack had negative center polarization. This means that the center conductor labeled as 3 which is shown in the pinout diagram in Figure 44 should be connected to ground. Pins 1 and 2 should both be connected to the input voltage. A multimeter was used to make sure that the center conductor was connected to ground on the circuit board and that the inner conductor was tied to VIN. After this was confirmed then the next step was to power it on with the power supply and troubleshoot it if any problems came up. Troubleshooting of the circuit is explained in the next section.

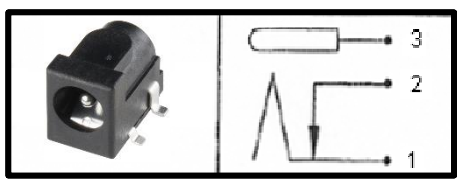

FIGURE 44

DC POWER JACK AND SCHEMATIC

XIV. TROUBLESHOOTING

After all the components were soldered onto the board, the first step was to power up the circuit with the LEDs connected to the output of the board. As soon as the power supply was connected, nothing happened to the circuit. The first thing was to check the actual voltage being provided by the supply by connecting a multimeter across VIN and PGND shown in Figure 29. I checked the socket by connecting a phone charger and seeing if it charged my phone. It did, so my next step was to verify that the power supply was working. I checked the voltage from the power supply and confirmed that it was working. I did a visual inspection of the board and everything seemed fine, so I did a continuity check with the multimeter at several points on the board. I immediately found out that the vias that I added to the ground plane shown below in Figure 45 with the black box around them were not actually connected to the power supply ground. This created no path for the current to flow through. This could have been easily solved before sending off the PCB to be manufactured by turning those vias into thermal vias so they could connect the top PGND plane with the ground plane. The problem was solved by soldering a small wire to one of the vias and soldered to the test point shown in Figure 45 with the green circle around it. Once this was done, the connection was tested with a multimeter.

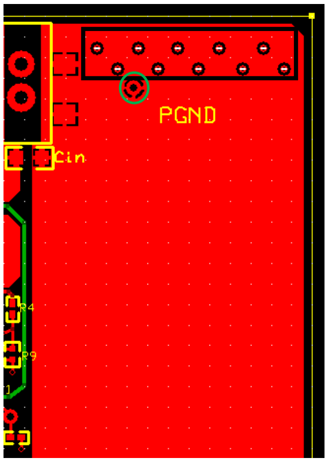

FIGURE 45

CIRCUIT BOARD PGND VIAS

The power supply was once again connected to the DC power jack and the circuit did not power on. I used the multimeter to check the voltages at various points on the circuit and saw that the chip was not being powered on. Upon inspecting the datasheet, it was suggested by my advisor to check the FLT pin of the IC. The FLT pin is an active-low, open-drain fault indicator that asserts when there is an overvoltage across the LED string, short-circuit condition across the LED string, or over temperature. OVP+ is the overvoltage protection pin, it sets the overvoltage threshold limit across the LEDs.

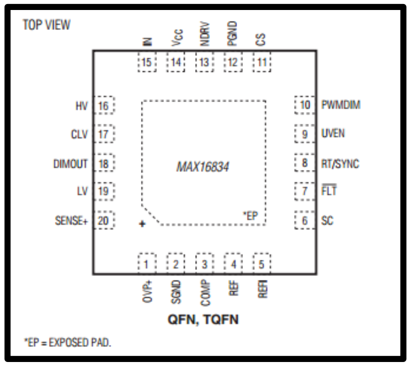

FIGURE 46
MAX16834 PIN CONFIGURATION

The OVP+ pin is pin 1 as shown in Figure 46. If the differential voltage across the pin is greater than 1.435V then the NDRV pin is disabled. The voltage across OVP+ was measured and turned out to be 0.26789V, which was well below the threshold. This ruled out the first case as being the problem. Next I checked the temperature of the IC with the thermal imager and did not see any overheating, so the third case was also ruled out as being the source of the problem. I also checked the voltage across pin 9 shown in Figure 46. Pin 9 is the UVEN input of the chip, it features an overvoltage protection circuit. If the voltage across UVEN exceeds 1.435V then the MAX16834 IC is turned on and the output is enabled, if it is lower, the output is disabled. The voltage across UVEN was 1.5734V which was above the threshold so the IC had to definitely be on but it wasn't. The last thing was to check for a short-circuit condition across the LEDs. The board was tested and there seemed to be no shorts, across the components. Since the IC contained its solder pads underneath the chip, I wasn't able to check properly for shorts across the pins. My advisor suggested that I check the melting point of the solder I was using and comparing it to the IC's reflow soldering temperature. I found out that the reflow soldering temperature was above the melting point of the solder by about 15˚C. He suggested that I use solder with a melting point higher than the reflow soldering temperature of the IC, I was not able to find any online. I decided to use solder paste that was found in the power electronics lab to solder the chip with one again. This time instead of putting it in the reflow oven, I decided to use the hot-air gun to solder it with. Once the solder melted and I let the board cool down, I went back and checked every solder point under the microscope. Everything looked good, so the next step was to try and power it once again with the power supply. Once the supply was connected to the DC power jack, the LEDs immediately turned on. Data could finally be obtained with the circuit providing power to the LEDS, so the next step was to take some measurements. This process is explained in section XV.

XV. RESULTS

Once the LEDs turned on, I went ahead and obtained some data from the working circuit. The first step was to make sure that the PWMDIM input worked to make sure that it was dimming the LEDs. The jumper was disconnected and a 3V peak-to-peak signal with a frequency of 100 kHz was input into one of the pins. The duty cycle was adjusted to 80% and then the photo cell shown in Figure 47 was connected to a multimeter to measure the current. The current of the photo cell is measured because it is directly proportional to the amount of light emitted by the source, but there is no conversion factor that relates both. Figure 48 shows how bright the LEDs appear when an 80% duty cycle signal is inserted to PWMDIM.

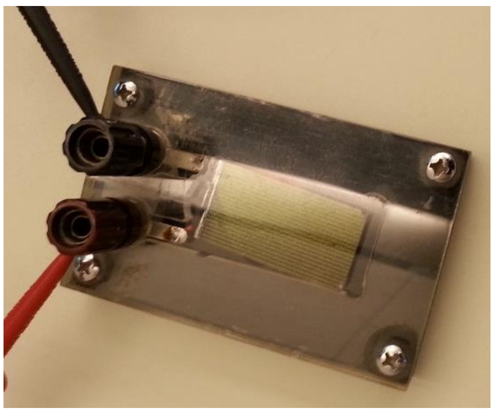

FIGURE 47
PHOTO CELL USED IN MEASURING CURRENT

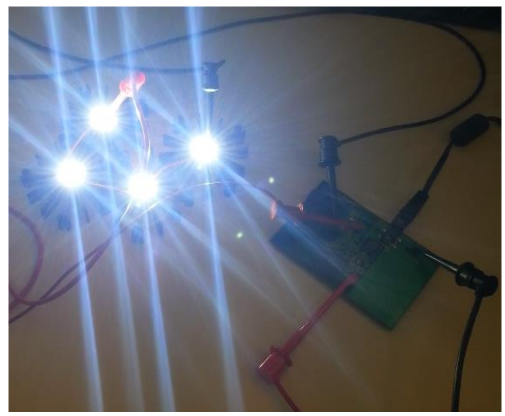

FIGURE 48
LIGHT INTENSITY WHEN DUTY CYCLE = 80%

The photo cell was then used to measure the current at the various duty cycle intervals shown in Table 14. A duty cycle of zero corresponds to the current measured when the circuit was off, so it was only detecting the lighting in the room. Just from the data shown in Table 14, it is confirmed that the intensity of the light increases as the duty cycle is also increased.

TABLE 14
PHOTO CELL CURRENT MEASUREMENTS

Duty Cycle (%)	Photo cell current (mA)
0	0.1775
20	1.0267
30	1.9475
40	2.3924
50	3.4735
60	4.3781
70	6.1168
80	6.7733

The data found in Table 14 was plotted and shown in Figure 49 just to see a visual representation of how much the intensity of the light increases as the duty cycle is changed by 10% intervals.

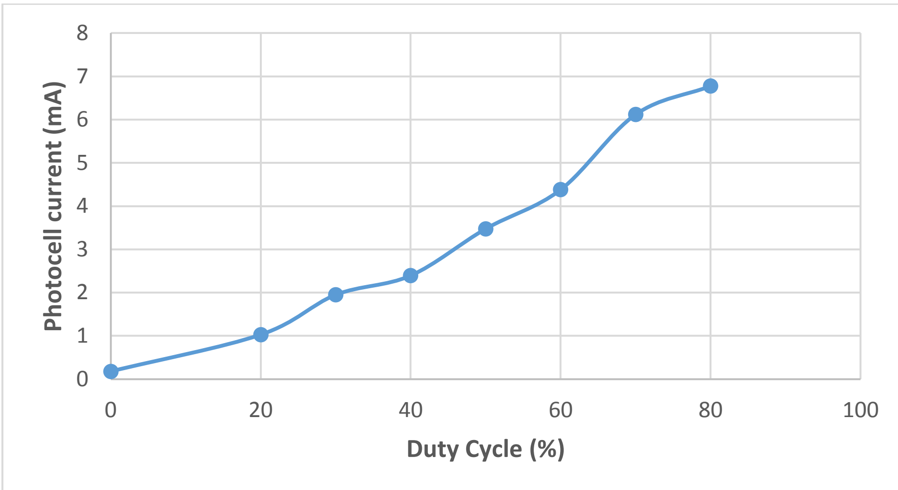

FIGURE 49

PHOTOCELL CURRENT VS DUTY CYCLE PLOT

Once the current of the photo cell was measured at each interval, the current and voltage of the LED string were measured at each interval of the duty cycle using a multimeter. The results are shown in Table 15.

TABLE 15

LED STRING CURRENT & VOLTAGE MEASUREMENTS

Duty Cycle	Voltage (V)	Current (mA)
20%	11.214	67.826
30%	11.605	139.36
40%	11.926	225.1
50%	12.186	324.65
60%	12.399	426.64
70%	12.818	736.84
80%	12.931	831.79

Figure 50 shows the NDRV output of the IC, NDRV is connected to the gate of the IC and the voltage drives the MOSFET Q1. From the datasheet it is specified that NDRV swings from VCC and PGND. In this case VCC is referring to VIN which is the input voltage of the power supply which turns out to be 5V. From Figure 50 one can see that the voltage swings from 5.1V to ground.

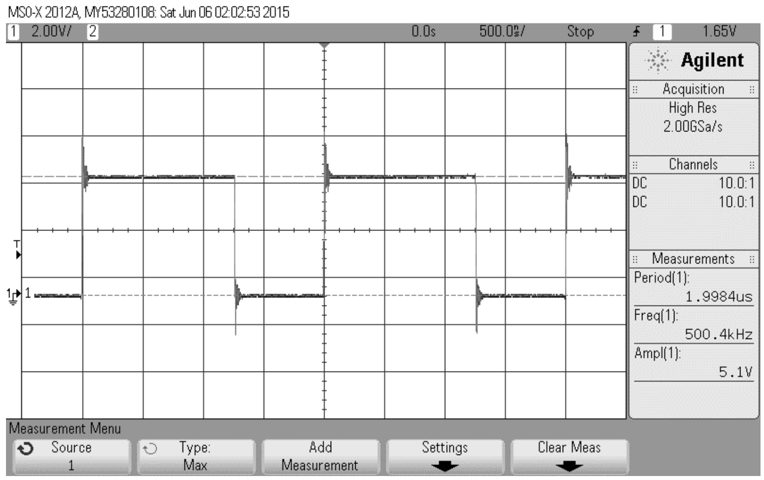

FIGURE 50

NDRV VOLTAGE

Figure 51 shows the voltage waveform taken at the source of Q1, it is also connected to the current-sense input CS. The voltage at CS is used to terminate the on pulse width of the switching cycle which allows for peak current-mode control.

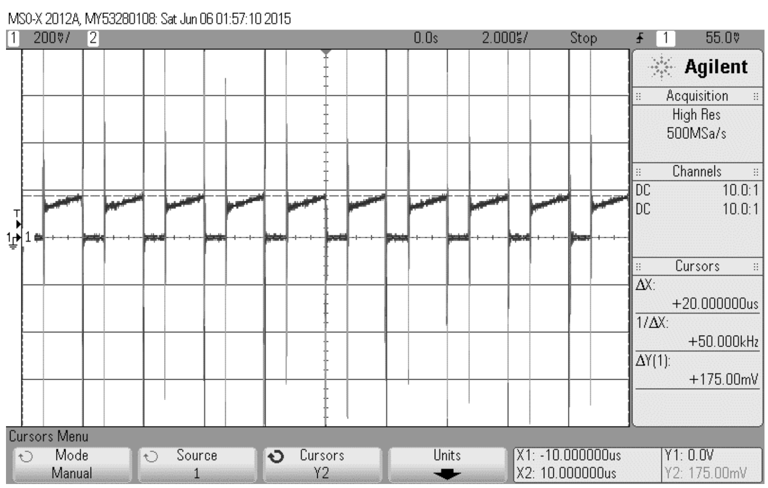

FIGURE 51

CS VOLTAGE

Figure 52 shows the voltage at the output of the inductor which is also connected to the drain of Q1. During each on state of the cycle the output voltage is seen across the inductor, the frequency is 498 kHz which is really close to the oscillating frequency of the IC which was programmed to be 500 kHz.

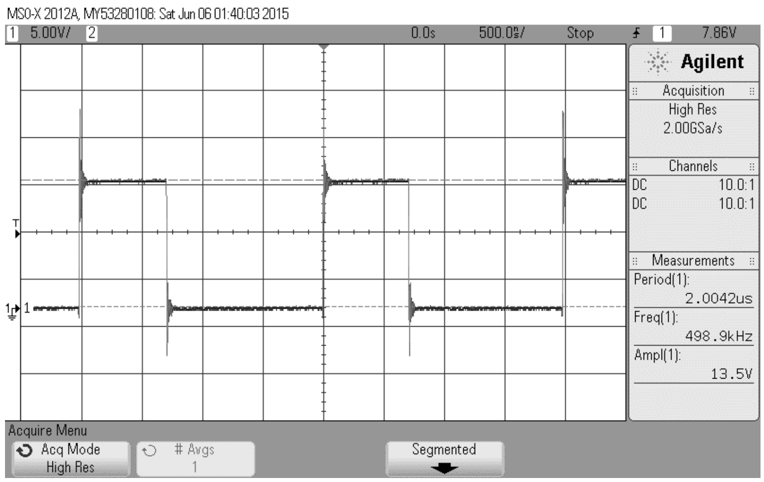

FIGURE 52

DRAIN VOLTAGE OF Q1

The power consumed by a typical incandescent lightbulb is about 60W. From Table 15, the total power consumed by the LEDs is about 10.76W at 80% duty cycle. This is six times less than the power consumed by the incandescent lightbulb. I was not able to measure the light intensity of the LEDs to verify that it met my initial requirements of a minimum of 800 lumens due to not having the right equipment to do so. 800 lumens is what a typical incandescent lightbulb emits, the system did appear to provide more light than a lightbulb but without actual values it cannot be verified.

Upon doing further research, I was able to find a 60W equivalent dimmable LED lightbulb. This type of bulb is manufactured by CREE which is also the manufacturer of the LEDs that I used in this project. The total cost of the project excluding labor, was $272. The cost of the dimmable LED bulb is $4.97. The dimming feature of the LED bulb cannot be used since most desk lamps do not contain a dimming feature or homes are also not equipped with dimming controls.

XVI. FUTURE WORK

There were a couple of additional features that I will be implementing to this project in the future. As I previously mentioned, I added a male header in between resistors 20 & 21 which is connected directly to PWMDIM. PWMDIM is a dimming input pin which needs to have a voltage higher than 1.435V in order to turn the dimming MOSFET on. When a jumper is added to the male headers, the LEDs can be powered directly from the reference voltage of the MAX16834 IC. When the jumper is removed, the LEDs can be dimmed by adding a PWM signal directly to one of the male headers and varying the duty cycle of the signal. The original idea was to obtain the varying PWM signal from a microcontroller as explained in section 11 but it can also be generated through a 555 timer IC.

I will be adding the whole project into an enclosure so that it more closely resembles a luminaire and I will also be placing the four heat sinks on a metal plate in order to mount the LEDs to the luminaire and in order to further dissipate heat. I will also be adding a switch to the project so that the driver can be turned off easily without having to play with the PWM in order to turn off the circuit. I will also look into purchasing a multimeter that contains a thermocouple in order to be able to measure the junction temperature of the LEDs and make sure that the heat sinks are keeping them well below their maximum value.

I will also look into adding a connector to each LED so that it can be easily removed in the case that one of them fails. Each LED is connected in series so if one of them were to fail, the rest of them would not work. I will also look into measuring the light output to make sure that it met my specifications.

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XVIII. APPENDICES

APPENDIX A. SENIOR PROJECT ANALYSIS

Project Title: Design of a High Powered LED Driver

Student's Name: Omar Renteria

Advisor's Name: David B. Braun

Summary of Functional Requirements

The LED driver provides power to set of high powered LEDs efficiently. The system provides greater luminous flux than CFL's or incandescent bulbs for a fraction of the cost.

Primary Constraints

A significant challenge for this project is going to be the overall area that the driving circuit takes up. The goal is to try and get it to be as small as possible without affecting its efficiency. A major constraint for this system will be the thermal management of the LEDs. Most of the electricity in an LED is converted to heat rather than to light. The efficiency of the LEDs will decrease with increased temperatures and they also run the risk of being permanently damaged. The junction temperature of the LEDs should be kept beneath 120˚C to maximize their lifetime. The junction is the area between the p- and n-type semiconductors that form the diode. The temperature at this junction can be reduced through the use of a heat sink so that it can operate efficiently.

Economic

The LEDs used in this circuit will provide a greater luminous flux than traditional lighting products such as CFLs or incandescent bulbs while consuming a lot less power than them [1]. It will affect the economy by saving the consumer money and therefore increasing their financial capital which could then be spent on other services or products. Natural capital decreases since the system requires resources which are found in nature in order to be manufactured. The system will seem like a huge investment to some consumers but it will eventually save the consumer money on their electric bills and maintenance of the LEDs. LEDs have a large lifespan which does not require them to be changed often. Both the consumer and the power distribution companies will benefit from the sale of this product as soon as it is sold. The consumer will save money on their electric bill and companies will earn money through "decoupling" according to their state mandates [12].

"Decoupling" separates the profits that a utilities company makes from their total electric or gas sales so that they do not try to sell more energy. This means that a utilities company will earn more when they sell less energy. The estimated development time for this project is shown in the Gantt chart shown in Figures 1-3. The total cost for this project is estimated to be around $4965. The details for the estimate can be found on Table 6. After the project is done, new features can be installed such as some sort of dimming control to allow the customer to control the brightness of the light.

If manufactured on a commercial basis

The number of devices sold per year is estimated to be low at first. The prediction is for around 500 units to be sold the first year that the product is introduced into the market. If the system were to be mass produced then the manufacturing cost for each unit is estimated to be around $120. Each unit includes the LED driver, the rectifier circuitry, the LEDs and heat sink which will all be assembled inside of a light fixture. The estimated purchase price for a consumer per device is going to be around $150. This value gives a profit of $30 per device sold and if 500 units are estimated to be sold the first year, then a profit of $15,000 is expected for the first year. The system is estimated to be on for at least 4 hours per day every year. This comes out to 11.68KWh of electricity used per year. At an estimated cost of about 18.12 cents per kilowatt-hour, the total cost of use per year would amount to a total of around $2.11. An incandescent bulb would require around 87.6KWh of electricity per year which would amount to a total cost of $15.87. A compact fluorescent bulb would require around 21.9KWh of electricity per year. The total cost for the electricity used would come out to around $3.97.

Environmental

The materials needed to produce this system have to be mined from the earth or recycled from old parts. Therefore it will affect the environment by depleting its resources. Since the circuit will be powered through the grid, then this means that the LED driver will indirectly contribute to the consumption of fossil fuels. This is because most power plants burn fossil fuels such as coal or oil to generate electricity. The system will also benefit the environment by providing a more efficient source of light which will prevent the waste of electrical power. The use of chemicals during the manufacturing process of the system can lead to harming the ecosystem if they are not disposed of properly.

Manufacturability

Manufacturing process will be somewhat easy since surface mount components are being planned for use in the circuit. The components are just mounted on the PCB which has solder paste on the pads and placed inside the reflow oven which melts the solder paste and keeps the components from falling off.

The final product will have to be thoroughly tested to make sure that it achieves its required specifications before it is sold. For example, the heat sink used for the LEDs will have to be tested in order to ensure that it is dissipating the heat produced by them so that they can function efficiently. The light output will be tested to ensure that it produces at least the minimum luminous intensity that it was designed for.

Sustainability

There is very little maintenance that needs to be done on the system. LEDs generally last around 50,000 hours or more [1]. At an average use of about 4 hours per day, the LEDs in the system would need to be replaced every 34 years. The LEDs will be somewhat hard to replace since they will be arranged in an array and soldered together. This problem can be solved simply by designing an enclosure that contains some sort of plug where each LED can easily be snapped in place or removed. The upgrade in the design of the system would require the price to increase in order to compensate for the new materials used. One upgrade that would definitely improve the design of the project would be to add a dimming feature to control the intensity of the light being produced.

Ethical

The first entry in the IEEE Code of Ethics states that an individual must accept responsibility in making decisions consistent with the safety, health, and welfare of the public. The system will require to be properly manufactured and tested in order to ensure that it operates safely and that it will not harm the consumers in any way. Since this product is design to be used inside of a home, it is best to use lead-free solder to provide the consumer with a product that will not harm their health. The third entry states that a member agrees to be honest and realistic in stating claims or estimates based on available data. For example, a measurement could not be made for the light intensity of this project since the necessary equipment was not at my disposal. Instead, a photocell was used to see how the current would change as the intensity of the light increased. My estimate of obtaining a system that could emit a minimum of 800 lumens could not be measured so I went ahead and stated my reasoning for it in the report. One mode of ethical thought known as Utilitarian Ethics states that the ethical corporate action is the one that produces the greatest good and does the less harm for all who are affected which refers to customers, employees, shareholders, the community, and the environment.

Health and Safety

One of the primary health concerns regarding the manufacturing of this device is whether to use leaded solder or lead-free solder to join the components to the printed circuit board. Leaded solder has a lower melting point and has a superb ability to act as a joining agent. Lead-free solder has a higher melting point which means that more heat is needed to achieve flow. Lead-free solder is a bit more expensive because of the added costs in producing it. Lead is very harmful to humans, and it can lead to poisoning when exposed to large quantities. Lead is toxic because it replaces other metals such as zinc, calcium, and iron in biochemical reactions. Even with the added costs, it is far safer to use lead-free solder in the manufacturing of this system to ensure the health and safety of the consumers. CFL bulbs contain mercury, which is very poisonous and even small amounts of it can be potentially dangerous in landfills. The use of LED technology will help to reduce the use of CFL bulbs and therefore reduce the environmental impact that CFL’s cause.

The use of LEDs will save energy and therefore reduce the amount of fossil fuels burned in order to produce the energy that it requires to operate. The pollution caused by the burning of the fuels will be decreased since the LEDs operate more efficiently.

Social and Political

This system will impact the residents of a typical household and the companies in charge of producing and distributing power. The residents will benefit from being able to use an alternate source of lighting with greater luminous flux than traditional lighting methods at only a fraction of the cost per year. This seems like it would have a negative effect on companies such as PG&E since the amount of electricity used is lower, but this is not the case. The profits that power distribution companies make is “decoupled” from their electricity sales in accordance to the state mandates. What this means is that as a decoupled utility, the company earns more money by saving electricity rather than by selling more. This system will negatively affect the companies that manufacture incandescent bulbs or other type of lower efficiency bulbs by replacing them with a more reliable product and far more efficient. Direct stakeholders for this system include customers, professors, and the workers producing the system. Indirect stakeholders will be the companies that produce the equipment and components used in this system. This system will benefit indirect stakeholders by increasing the demand for their products, therefore increasing their profits.

Development

A new technology that will be used for this project is the use of surface mount components. Surface mount components are typically smaller than through-hole components because they have smaller leads or no leads at all. The use of this technology will allow the driving circuit to be as small as possible and have a reduced weight. The components are attached to the PCB through a reflow soldering oven. Solder paste is applied to the solder pads on the circuit board and the components are then placed on the board. The board is placed into an oven which melts the solder paste and surface tension of the melted solder automatically aligns the components on the board. This allows for a much cleaner soldered board than if it was done by hand with through-hole components. One valuable lesson that I learned as I went along with the project, was to read the datasheets carefully. My simulation did not work the first time I tried, since I did not read that a particular pin needed to be active high in order to turn the IC on. I was able to learn how to carefully solder small components with the use of a hot-air gun. I learned that the melting temperature of the solder used should be taken into account when trying to solder certain components such as the IC. I did not look into this and my IC was not soldered to the board properly.

APPENDIX B. PSPICE CODE

```
* MAX16834 MACROMODEL
* ----------------------------
* Revision 1.0 03/2009
* ----------------------------
* Model Platform: Spice3
* ----------------------------
* The MAX16834 is a current-mode high-brightness LED (HB LED) driver for
boost, buck-boost,
* SEPIC, and highside buck topologies. In addition to driving an n-channel
power MOSFET
* Switch controlled by the switching controller, it also drives an n-channel
PWM dimming switch
* to achieve LED PWM dimming. The MAX16834 integrates all the building blocks
necessary to
* implement a fixed-frequency HB LED driver with wide-range dimming control.
*
* ----------------------------
* Sub circuit name: MAX16834
* ----------------------------
* Connections: Model pin names are same as the device pin names.
* ----------------------------
* Parameters and features modeled.
* 1) UVEN threshold at 1.435 with 200mV hysteresis
* 2) PWMDIM threshold at 1.435 with 200mV hysteresis
* 3) OVP threshold at 1.435 with 200mV hysteresis referenced to LV pin
* 4) 3.7V REF output 10mA maximum load
* 5) 7V VCC with 50mA maximum load
* 6) 5V CLV regulator referenced to LV with 3mA maximum load
* 7) Oscillator with frequency setting by resistor RT pin to GND
* 8) Current mode PWM controller
* 9) NDRV driver
* 10) Floating LED current sense and DIMOUT driver
* 11) LED over current protection and Hiccup mode
* 12) Fault indication
* 13) Peak current sense delay and blanking. PWM dimming delay
* ----------------------------
* Parameters and features not modeled.
* 1) Feedback loop parameters of VCC, REF and CLP
* 2) External frequency synchronization
* 3) Over current trip and hiccup mode
* 4) Over the Temperature characteristics
* * ----------------------------
* NOTES:
* 1) A 3mS simulation at 500 kHz switching frequency takes approximately
*    15 minutes in a 3GHz system.
* 2) Hiccup time is reduced to 1/10th to make simulation faster
*************************************************
.SUBCKT MAX16834 OVP+ SGND COMP REF REFI SC FLTB RT
+UVEN PWMDIM CS PGND NDRV VCC IN HV CLV DIMOUT LV SENSE+
*************************************************
*UVLO1 (3.5V-ON, 3.45V-OFF, 0.05V Hysteresis)
VUV VUV2 GND 3.5V
GUV GND UV1 POLY (2) IN VUV2 UV1 GND 0 1M 0.05M
XDUV1 GND UV1 DA1
```

```
CUV UV1 GND 10P
XDUV2 UV1 V1 DA1
VUV1 V1 GND 1V
*************
*UVEN
XUVEN UV2 GND UVEN CMP1435MV
EUVEN UVINT GND POLY (2) UV1 GND UV2 GND 0 0 0 0 1
RL2 UV2 GND 1MEG
*************
*PWMDIM INPUT
XPWMIN PWMI GND PWMDIM CMP1435MV
RLP1 PWMI GND 1MEG
*************
*AND GATE
EFLTB FLTI1 GND FLTI GND 1
EPWM PWMI1 GND PWMI GND 1
RPA1 V1 PW1 10K
XDAP1 PW1 FLTI1 DA1
XDAP2 PW1 PWMI1 DA1
*************
*OVP INPUT
XOVP OVPI LV OVP+ CMP1435MV
VL1 V1L LV 1V
EOVP1 FLTA GND V1L OVPI 1
RLO1 OVPI GND 1MEG
*************
*3.7V REFERENCE
EVIN1 VIN1 GND IN GND 1
RVIN1 VIN1 REF1 10K
VREF1 REF2 GND 3.7V
XDREF1 REF1 REF2 DA1
EREF REF4 GND POLY (2) REF1 GND UV2 GND 0 0 0 0 1
XDREF2 REFA REF4 DA1
IREF REF4 REFA 30MA
CREF REF4 REFA 100P
RREF2 REFA REF 50M
*************
* 7V VCC LDO
HVIN2 VIN1 VIN2 VLDCS 16.5
RVIN VIN2 VCC1 10K
XDVCC1 VCC1 VCC2 DA1
VCC1A VCC2 GND 7.0V
EVCC1 VCC3 GND POLY (2) VCC1 GND UV2 GND 0 0 0 0 1
RVCC1 VCC3 VCC4 1.95
IVCC VCC4 VCC5 80M
XDCC2 VCC5 VCC4 DA1
VLDCS VCC5 VCC6 0V
XDCC3 VCC6 VCC DA1
*************
* 5V CLV LDO
EHV1 HV1 LV HV LV 1
RHV1 HV1 HV2 10K
V5V1 LV5V LV 5V
XDLV1 HV2 LV5V DA1
ECLV CLV1 LV POLY (2) HV2 LV UV2 GND 0 0 0 0 1
RCLV1 CLV1 CLV2 29
XDLV2 CLV CLV2 DA1
```

```
ICLV CLV2 CLV 3.5MA
*************
*OSCILLATOR
ERT RT1 GND UVINT GND 1.2
XDRT1 RT2 RT1 DA1
IRT1 RT1 RT2 0.3MA
XDRT2 RT2 RT3 DA1
VRT1 RT3 RT 0V
COS2 RT4 GND 118.8P
FOSC GND RT4 VRT1 1
XDOSC3 GND RT4 DA1
ROSC1 RT4 GND 10MEG
****
VOS1 OS1 GND 2.1V
GOS1 GND OS2 POLY (2) RT4 OS1 OS2 GND 0 1M 2.0M
COS1 OS2 GND 1P
XDOS1 GND OS2 DA1
XDOS2 OS2 V1 DA1
MOS1 RT4 OS3 GND GND MN1 L=0.5U W=49.1U
EOS1 OS3 GND OS2 GND 2
*************
*CURRENT SENSE
RCS1 CS CS1 5K
MOS2 CS1 BL2 GND GND MN1 L=0.5U W=50U
*60NS BLANKING
V051 V05 GND 0.5V
CBL1 ND1 ND2 86.7P
RBL1 ND2 GND 1K
XDBL1 GND ND2 DA1
GBL1 GND BL1 POLY (2) ND2 V05 BL1 GND 0 1 1M
CBL2 BL1 GND 1P
XDBL2 GND BL1 DA1
XDBL3 BL1 V1 DA1
EBL1 BL2 GND BL1 GND 2
*************
*SLOP COMP
GSLP GND SC ND1 GND 100U
XDSLP1 GND SC DA1
END2 ND3 GND ND1 GND 2
XDSLP2 SC ND3 DA1
*************
*SIGNAL FOR PWM COMP
ECS CS3 GND POLY (2) SC GND CS1 GND 0.65 1 1
*PWM COMP
GPW1 GND PW5 POLY (2) CS3 COMP PW5 GND 0 100M 1M
RPW3 PW5 GND 1MEG
CPW1 PW5 GND 1P
XDP1 PW5 V1 DA1
XDP2 GND PW5 DA1
*CURRENT LIMIT COMP
VCM CM3 GND 0.3V
GC1 GND CM5 POLY (2) CS1 CM3 CM5 GND 0 100M 1M
RC3 CM5 GND 1MEG
CCM1 CM5 GND 1P
XDC1 CM5 V1 DA1
XDC2 GND CM5 DA1
*************
```

```
*CS AMP
VREF2 V25 GND 2.5V
GLA GND EAN POLY (2) SENSE+ LV UVINT GND 0 0 0 0 9.9M
RLA EAN GND 1K
XDLA1 GND EAN DA1
XDLA2 EAN V25 DA1
*ERROR AMP
EREF2 V37 GND REF GND 1
GEA1 GND EAOUT REFI EAN 500U
XDEA1 GND EAOUT DA1
XDEA2 EAOUT V37 DA1
REA1 EAOUT GND 2MEG
CEA1 EAOUT GND 10P
*************
*SWITCH
MS1 EAOUT PWM1 N1 N1 MN1 L=0.5U W=50U
MS2 COMP PWM1 N1 N1 MN1 L=0.5U W=50U
CN1 N1 GND 0.1P
ES1 PWM1 N1 PW1 GND 2
*************
*OR GATE
EPW1 PW5A GND PW5 GND 1
ECM1 CM5A GND CM5 GND 1
XDOR1 PW5 OR1 DA1
XDOR2 CM5 OR1 DA1
ROR1 OR1 GND 10K
*************
*FLIP-FLOP
VF1 FF2 GND 0.5V
GF1 GND FF1 FF1 FF2 1M
CF1 FF1 GND 2P
XDF1 GND FF1 DA1
XDF2 FF1 V1 DA1
**
GFSET GND FF1 OS2 GND 2M
GFRST FF1 GND OR1 GND 4M
GEN FF1 GND V1 UVINT 5M
*AND GATE
GAN1 GND NDR1 POLY (4) V1 FF1 V1 PW1 V1 FLTA OS2 GND 1M -2M -2M -2M -2M
XDA1 GND NDR1 DA1
XDA2 NDR1 V1 DA1
CAN1 NDR1 GND 0.2P
*PROP DELAY 70nS
EPR PR1 GND NDR1 GND 2
RPR1 PR1 PR2 1K
T1 PR2 GND PR3 GND ZO=1K TD=40N
RPR2 PR3 GND 1K
CPR3 PR3 GND 0.5P
END1 ND1 GND PR3 GND 1
*************
*MOSFET DRIVER
EDRV1 DR1 GND POLY (2) V1 PR3 VCC GND 0 0 0 0 1
XDDR1 DR1 DR2 DA1
RDR1 DR1 DR2 40
CDR1 DR2 GND 10P
XDDR2 DR3 DR1 DA1
RDR2 DR3 DR1 40
```

```
CDR2 DR3 GND 10P
MDR1 NDRV DR2 VCC VCC MP1 L=0.5U W=1.3M
MDR2 NDRV DR3 GND GND MN1 L=0.5U W=580U
*************
*DIM DRIVER
EDMV1 DM1 LV POLY (2) V1 PW1 CLV LV 0 0 0 0 1
XDDM1 DM1 DM2 DA1
RDM1 DM1 DM2 40
CDM1 DM2 LV 10P
XDDM2 DM3 DM1 DA1
RDM2 DM3 DM1 40
CDM2 DM3 LV 10P
MDM1 DIMOUT DM2 CLV CLV MP1 L=0.5U W=47U
MDM2 DIMOUT DM3 LV LV MN1 L=0.5U W=23U
*************
*FAULT INDICATION
GFLT1 GND FLT3 POLY (2) V1 FLTA V1 FLTI 1M -2M -2M
XDFL1 GND FLT3 DA1
XDFL2 FLT3 V1 DA1
CFL1 FLT3 GND 1P
EFLT1 FLT4 GND V1 FLT3 3
MFLT1 FLTB FLT4 GND GND MN1 L=0.5U W=50U
*************
*FAULT_B
*SENSE >0.3V AT SENSE+
GFCMP1 GND FC1 POLY (2) SENSE+ LV FC1 GND -300U 1M
CFC1 FC1 GND 1P
XDFC1 GND FC1 DA1
XDFC2 FC1 V1 DA1
EFC1 FC2 GND FC1 GND 2
R5US FC2 FC3 1K
XD5US FC3 FC2 DA1
C5US FC3 GND 7.15N
***
GFCMP2 GND FC4 POLY (2) FC3 V1 FC4 GND 0 1M 10U
CFC2 FC4 GND 1P
XDFC3 GND FC4 DA1
XDFC4 FC4 V1 DA1
*************
VFC1 FC8 GND 0V
*************
*REFHI
XREFHI REFHI GND LV CMP1435MV
RLF3 REFHI GND 1MEG
*************
*HICCUP MODE
EHU1 HU1 GND POLY (2) REFHI GND FC8 GND 0 0 0 0 1
EHU2 HU2 GND POLY (2) V1 REFHI FC4 GND 0 0 0 0 1
EHU3 HU3 GND POLY (2) HU1 GND HU2 GND 0 2 2
CHU1 HU3 HU5 1N
RHU1 HU5 GND 1K
XDHU2 GND HU5 DA1
EHU4 HU6 GND HU5 GND 1
XDHU1 HU6 HU7 DA1
CHU2 HU7 GND 10N
FHU1 HU7 GND VRT1 0.102
***
```

```
GHU1 GND HU8 POLY (2) HU7 V1 HU8 GND 0 1M 10U
CHU33 HU8 GND 1P
XDHU3 GND HU8 DA1
XDHU4 HU8 V1 DA1
EHU5 FLTI GND V1 HU8 1
*************
**********
VG1 GND SGND 0V
VG2 GND PGND 0V
RCLG1 LV SGND 0.1G
**************************************************
.MODEL MP1 PMOS (VTO=-1.0 KP=50E-6)
.MODEL MN1 NMOS (VTO=1.0 KP=100E-6)
.MODEL DB D (IS=100E-14 CJO=1P)
**************************************************
.ENDS MAX16834
**************************************************
.SUBCKT DA1 1 2
D1 1 3 DB
ED1 3 4 3 1 0.999
R2 4 2 10M
RP 1 2 1G
CDA 1 2 1P
.MODEL DB D (IS=100E-14 CJO=1F)
.ENDS
**************************************************
.SUBCKT CMP1435MV CM1 GND IN
RIN IN GND 1.5MEG
VCM VCM2 GND 1.435V
GCM GND CM1 POLY (2) IN VCM2 CM1 GND 0 1M 0.2M
XDCM1 GND CM1 DA1
CCM CM1 GND 5P
XDCM2 CM1 V1 DA1
VCM1 V1 GND 1V
.ENDS
**************************************************
```

```
*si2318DS MACROMODEL
*March 21, 2005
*Doc. ID: 78869, S-50383, Rev. B
*File Name: Si2318DS_PS.txt and Si2318DS_PS.lib
.SUBCKT Si2318DS 4 1 2
M1 3 1 2 2 NMOS W=854711u L=0.25u
M2 2 1 2 4 PMOS W=854711u L=0.45u
R1 4 3     RTEMP 21E-3
CGS 1 2      420E-12
DBD 2 4      DBD
****************************************************************
.MODEL NMOS       NMOS (LEVEL = 3            TOX    = 5E-8
+ RS      = 11E-3          RD      = 0           NSUB    = 2.8E17
+ KP      = 1.2E-5         UO      = 650
+ VMAX    = 0              XJ      = 5E-7        KAPPA = 1E-2
+ ETA     = 1E-4           TPG     = 1
+ IS      = 0              LD      = 0
+ CGSO    = 0              CGDO    = 0           CGBO    = 0
+ NFS     = 0.8E12         DELTA = 0.1)
****************************************************************
.MODEL PMOS       PMOS (LEVEL = 3            TOX    = 5E-8
+NSUB     = 2E16           TPG     = -1)
****************************************************************
.MODEL DBD D (CJO=150E-12 VJ=0.38 M=0.30
+RS=0.1 FC=0.5 IS=1E-12 TT=5E-8 N=1 BV=40.5)
****************************************************************
.MODEL RTEMP RES (TC1=7E-3 TC2=5.5E-6)
****************************************************************
.ENDS
```

```
*ss2p4 MACROMODEL
**********************************
* Copyright:                     *
*   Thomatronik GmbH, Germany    *
*   info@thomatronik.de          *
**********************************
*   PSPICE
.subckt ss2p4 1 2
ddio 1 2 legd
dgr 1 2 grd
.model legd d is = 7.07124E-005 n = 1.49383 rs = 0.0453563
+ eg = 0.597561 xti = 1.22745 t_measured = 27
+ cjo = 2.93259E-010 vj = 0.7 m = 0.490878 fc = 0.5
+ tt = 1.4427E-009 bv = 44 ibv = 50 af = 1 kf = 0
.model grd d is = 4.83671E-015 n = 1.15567 rs = 0.0281331
+ eg = 1.79827 xti = 0.491328 t_measured = 27
.ends
```

```
*CREE X-RE LED MACROMODEL
.MODEL XRE D
+ IS=1E-5
+ N=12.4041
+ RS=.2
+ XTI=45.900
+ EG=2.5000


*LED Driver Project Netlist
* Source DRIVER
X_U1          Y 0 N4 N1 N2 N16547 G N15820 N3 DIM S1 N60929 G1 N14515 VIN
N14515
+ N5 GATE 0 SOURCE MAX16834
C_C5          N14515 0 2.2u TC=0, 0
C_C4          0 N1 0.15u TC=0, 0
C_C2          0 N16547 2400p TC=0, 0
R_R10          0 SOURCE 0.1 TC=0, 0
R_R3          0 N15820 10k TC=0, 0
R_R6          N2 N1 9.1k TC=0, 0
R_R5          0 N2 2.1k TC=0, 0
C_C1          0 VIN 6.8u TC=0, 0
R_R1          N3 VIN 30k TC=0, 0
R_R2          0 N3 13k TC=0, 0
C_C7          N20019 N4 .2u TC=0, 0
R_R7          0 N20019 48.3401 TC=0, 0
C_C6          0 N5 0.47u TC=0, 0
R_R4          Y DRAIN 17.8k TC=0, 0
R_R9          0 Y 1k TC=0, 0
C_C3          0 DRAIN 15u TC=0, 0
V_V1          VIN 0 5Vdc
R_R11          G N1 10k TC=0, 0
R_R8          0 S1 0.07 TC=0, 0
C_C8          0 SOURCE .22u TC=0, 0
X_U2          D1 DRAIN SS2P4
X_Q1          D1 G1 S1 SI2318DS
D_D1          DRAIN N30262 XRE
D_D2          N30262 N30358 XRE
D_D3          N30358 N30456 XRE
D_D4          N30456 LED- XRE
X_Q2          LED- GATE SOURCE SI2318DS
L_L1          VIN D1 10uH
R_R12          N60929 0 1m TC=0, 0
C_C9          DRAIN LED- 100u TC=0, 0
C_C10          DRAIN LED- 100u TC=0, 0
R_R13          DIM N1  10k TC=0,0
R_R14          0 DIM  100k TC=0,0
```